4. Chapter Four, Safety Analysis

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4.1. Introduction

The design of the Collider Accelerator Department's suite of ion injectors, accelerators, the collider and the experimental facilities is based upon the experience and successful designs employed since the initial startup of the AGS in 1960. The basic approach for the safety analysis has been to review the potential hazards for each major segment of the facility. Hazard analysis is the standard method for applying the DOE graded approach for minimizing risk. It is well suited to identifying and understanding risk because it requires consideration of both the likelihood and the potential consequences of hazards. The product of likelihood and consequence constitutes the risk. When using risk as the measure of acceptance, the allowable consequences for lower likelihood events are higher than for the higher likelihood events. In the hazard analyses presented in this chapter, the approach has been to evaluate the risk and to identify preventive and mitigating features and controls that ensure that risk is acceptably low. Because the suite of facilities follows consensus codes and standards, standard industrial hazards are adequately addressed and their risks minimized without the need for detailed hazard analyses.

4.2. Hazard Analysis Approach

Hazard analyses include hazard identification and screening, assessment of the potential consequences of unmitigated risk, identification of relevant and effective mitigation/preventive measures, and finally, assessment of mitigated risk. Hazard analysis makes it possible to understand the risk and make informed risk acceptance decisions. It is desirable to be able to show that the C-AD Facility risks are in the "extremely low" category (see Table 4.2), and an effort to do so has been made in this section of the SAD. The hazard identification process used the C-AD Facility design and operating information; BNL site documents; facility walk-downs to identify potential hazards within the complex that could adversely affect the workers and environment; and discussions with the engineers and users of the facilities. The hazards evaluation process is a largely qualitative assessment of potential accidents or impacts in terms of hazards, initiators, likelihood estimates, preventive or mitigating features and public, environmental and worker consequence estimates. A maximum credible accident scenario for each major portion of the complex is presented later in this chapter, the consequences of which bound all those to workers, the public and the environment. The results of these analyses confirm that the potential risks from operations and maintenance are extremely low. The hazards involve those present at all high-energy ion accelerators and experiments such as radiation, chemical, biological, electrical, magnetic fields, rf fields, energy sources, pressure and vacuum, material handling and lifting, heights, rotating equipment, fire, explosions, natural phenomena, steam, heat and cold, confined spaces, lasers, compressed gas, hazardous materials handling, etc. There are no unique hazards that are not addressed in a safe and efficient manner.

Table 4.2 The Risk Matrix

Consequence Level

High (Note 1)	Low Risk – Acceptable	Medium Risk- Unacceptable	High Risk- Unacceptable	High Risk- Unacceptable
Medium	Extremely Low Risk - Desirable	Low Risk – Acceptable	Medium Risk- Unacceptable	High Risk- Unacceptable
Low	Extremely Low Risk - Desirable	Extremely Low Risk - Desirable	Low Risk – Acceptable	Medium Risk- Unacceptable
Extremely Low	Extremely Low Risk - Desirable	Extremely Low Risk - Desirable	Extremely Low - Desirable	Low Risk – Acceptable
	Extremely Unlikely (<10^{-4}/y)	**Unlikely (Between 10^{-4}/y and 10^{-2}/y)**	**Anticipated (Note 2) Medium (Between 10^{-2}/y and 10^{-1}y)**	**Anticipated (Note 2) High (>10^{-1}y)**

Likelihood of Occurrence

Note 1: Definition of Consequence Levels -

- Extremely Low: Will not result in a significant injury or occupation illness or provide a significant impact on the environment.
- Low: Minor onsite with negligible or no offsite impact. Low risk events are events that may cause minor injury or minor occupational illness or minor impact on the environment.
- Medium: Medium risk events are events that may cause considerable impact onsite or minor impact offsite. Medium risk events may cause deaths, severe injuries or severe occupational illness to personnel or major damage to a facility or minor impact on the environment. Medium risk events are events from which one is capable of returning to operation.
- High: High-risk events may cause serious impact onsite or offsite. High-risk events may cause deaths or loss of facility/operation. High-risk events may cause significant impact on the environment.

Note 2: 10CFR835 may require limits that are more stringent for anticipated events.

4.3. General Approach to Risk Minimization

Hazard identification produces a comprehensive list of hazards present in a process or facility, and the screening phase removes all hazards that are below a threshold of concern, or that are covered by recognized industrial codes and standards. The hazards that are "screened out" do not need to be studied in detail because their risks are already well understood and acceptable. This process is a creative, multi-person examination of the processes, operations and experiments related to C-AD facilities. A hazard is a source of danger with the potential to cause illness, injury or death to personnel, damage to an operation or cause environmental damage.

For each screened hazard retained for further detailed hazard analysis, the unmitigated risk is first evaluated in terms of likelihood and consequence. This evaluation is performed using professional engineering judgment based on machine and experiment design and operating history. This places the hazard on the risk matrix (see Table 4.2). The following assumptions govern the determinations of unmitigated risk:

- The unmitigated risk does not include safety or control systems.
- Assigned frequencies are based on engineering judgment.
- Assigned consequence can be qualitative, but must be conservative.
- If the unmitigated risk is extremely low, then the analysis can stop at this point. Otherwise, one proceeds to the evaluation of mitigated risk as described below.

The unmitigated risk is reevaluated considering the preventive and mitigating factors in place that would either reduce the consequence or reduce the frequency. This should move the location on the risk matrix based on assumed conditional probabilities of failure for the mitigating systems. At this point, the mitigated risk should be either low or extremely low. For low risk, the evaluation of the hazard is reviewed to determine if there are additional preventive or mitigating features that could be credited to bring the risk to extremely low. The last step is to determine if it is necessary to designate any Safety-Significant equipment, make commitments for formal administrative controls, or specify limits for operation. Safety-Significant equipment is designated as such because it actively or passively protects workers and/or staff from significant hazards.

The purpose of Safety-Significant designation is to highlight a minimum number of structures, systems or components needed to ensure safety. The number of designated Safety Significant items and administrative controls and limits must be minimized so that they can be treated specially and considered for incorporation in the Accelerator Safety Envelope (ASE), appropriate procedures and/or quality assurance documents.

If the unmitigated consequence is fatal for one or more persons or a significant environmental impact can occur, then a Safety-Significant designation, in general, should be made. If there are several mitigating or preventive features, and any single one can control the hazard adequately, then it may not be necessary to designate a Safety-Significant feature.

Table 4.2 allows binning of the hazardous event by its risk, which is a combination of the consequence of the hazardous event and its likelihood of occurrence. Some of these combinations are deemed acceptable, meaning these lower risk bins are adequately addressed by the qualitative hazard evaluation process. Other, higher risk bins are labeled unacceptable because the accidents within these bins require additional quantitative analysis to determine the true mitigated risk.

4.4. Risk Minimization Approach for Radiation Hazards

The risk of a serious radiation injury at BNL accelerators and experiments is insignificant. However, for radiation exposure it is customary to go beyond the scope of Hazard Analysis to demonstrate that transient events, such as credible beam faults, do not cause annual radiation dose goals or requirements to be exceeded. The special status of radiation hazards is exemplified in the As Low As Reasonably Achievable (ALARA) requirement in the BNL Radiation Control Manual that exposure to radiation is to be minimized and driven as far below the statutory limits as is practicable. Some areas are controlled access areas. These areas (Controlled Area, Radiation Area, etc.) are established to control the flow and behavior of workers in each area such that workers receive the minimum radiation exposure coincident with operating and maintaining the facility, which is the risk, to achieve its authorized research mission, which is the benefit. These areas are set with the expectation that radiation levels will not exceed certain specified maxima depending on the type of zone. The designated area maxima will be satisfied considering both the base level of residual radiation fields and the integrated effect of the short bursts typical of credible beam faults. The C-A Operations Procedure Manual, in compliance with the BNL Radiation Control Manual, lists the different areas including the required controls for minimizing exposure to external radiation. Significant contamination and internal uptake of radionuclides at C-AD facilities is extremely unlikely. Further analyses of these issues are not necessary, and are documented in a Technical Basis for Bioassay.[1]

[1] Technical Basis for Bioassay Requirements, Collider-Accelerator Department, January 2001.

4.5. Hazard Identification and Hazard Analysis

This section describes the hazard identification and qualitative hazard analysis for each of the major portions of the C-AD accelerators and experiments: injectors, accelerators, beam transport systems, beam stop systems, targets, support buildings, power supply buildings, cooling water systems, cryogenic systems, vacuum systems, shielding and instrumentation systems. The results of the hazard identification and analyses are given in Appendix 2.

The hazard identification process examined the C-AD facility processes, operations and maintenance that could result in a source of danger with the potential to cause illness, injury or death, damage to operations or environmental damage. The facilities design documentation, BNL conventional and radiological safety requirements, facility walk downs, C-A Operating and Emergency Procedures, and discussions with engineering staff, experimenters and safety professionals were utilized to conduct the detailed hazard identification and hazard analysis.

4.5.1. Conventional and Environmental Hazards

A review of all safety and health issues related to C-AD facilities leads to the conclusion that fire including explosions, radiation, oxygen deficiency hazards from large quantities of inert gases and electrical hazards require further safety analysis, which considers the preventive and mitigating facility design features. Hazard screening is documented in Appendix 2.

Pressure and vacuum vessels, use of toxic, hazardous and biological materials, use of small quantities of flammable/inert/cryogenic gases/fluids, noise, hoisting/rigging, confined space entries, lasers, rotating equipment, heat and magnetic fields are considered routine activities. The risks from these activities are maintained acceptable by compliance with the requirements of the BNL Standards Based Management System (SBMS) Subject Areas and the C-A Operations Procedure Manual. When required, these hazards undergo review by the appropriate BNL or C-AD committee or they undergo review by C-A ESHQ Division specialists during the work planning process, as indicated by C-A OPM or SBMS requirement.

Because of special focus on beryllium, lead and asbestos hazards, details of the programs controlling these hazards are summarized. The inhalation of beryllium dust or particles can cause chronic beryllium disease (CBD) and beryllium sensitization. The Department of Energy has established regulations to require a chronic beryllium disease prevention program (CBDPP) for certain work conditions. The goal of the CBDPP is to reduce the number of workers currently exposed to beryllium, minimize the levels of exposure to beryllium, and establish medical surveillance requirements to ensure early detection and treatment of disease. In 1997 and 1999 BNL conducted reviews of the use of beryllium on-site. These evaluations determined the applicability of BNL current operations to DOE regulations and led to the establishment of BNL policy on the use and handling of beryllium. Certain work at C-AD facilities involves beryllium. For this work, in accordance with BNL SBMS, a beryllium use review form (BURF) is required. These forms provide the precautions to be followed, PPE requirements and spill, release and cleanup plans for beryllium use and handling activities.

Lead is a toxic substance that, if not handled properly, can create adverse health effects. The inhalation or ingestion of lead dust or particles can cause permanent health effects in children and adults. The OSHA, HUD, and EPA have established regulations to require a lead exposure prevention program for certain work conditions. The goal of these requirements is to reduce worker levels of exposure to lead, establish medical surveillance requirements to ensure early detection and treatment of disease, and minimize releases to the environment. Procedures describe measures such as PPE to enable compliance with these regulations and to prevent worker injuries and illnesses from working with lead.

Asbestos may be present in many buildings at BNL, primarily in pipe insulation, ceiling tiles, gaskets, thermal insulation, cement boards and pipes, flooring material, and in roofing products. It may also exist in brake and clutch linings. It may also be found in some laboratory equipment (such as insulation on gloves, ring stand clamps, and heating mantles), fire blankets, and some older electrical wiring insulation.

Asbestos sampling and removal are highly regulated by government agencies such as the Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA). Conducting any operation that disturbs or removes asbestos requires written exposure control procedures that are approved by the BNL asbestos subject matter expert.

These procedures provide information on how to identify, sample, remove, dispose of, and work with asbestos-containing materials. This information ensures compliance with OSHA while protecting workers and building occupants. The procedures also provide information for the types of documentation that are involved in asbestos work. Asbestos workers must receive training that complies with the OSHA and EPA model training program curriculum.

Under certain conditions, usually associated with heavy occupational exposures over prolonged periods, asbestos can lead to diseases such as asbestosis, mesothelioma, and lung cancer. Based on both animal and human studies, asbestos is classified as a Class I carcinogen (known to be human carcinogens) by the International Agency for Research on Cancer (IARC). The nature of the risks of asbestos exposure vary according to the duration and intensity of exposure, the type of fiber, and other critical factors. By controlling airborne fiber release and exposure to workers and building occupants, the risk of these asbestos diseases can be greatly reduced.

Electrical safety is a serious and complex subject, which is controlled by trained and experienced C-A and BNL staff engineers, operators, technicians and maintenance personnel. A full description of the electrical safety requirements that assure electrical safety is given in the BNL SBMS. At times access to the injectors, accelerators, transport lines, target areas and the collider is allowed when the magnets are powered. However, access to these areas is always controlled and limited to properly trained individuals. A C-A OPM procedure and an approved working hot permit cover access to these areas by trained and authorized C-A support staff to investigate problems.

Static or fringe magnetic fields that are present in the facility magnets do not warrant special controls other than appropriate warning signs and training of personnel who have access to the areas in accordance with the requirements of the BNL SBMS.

Lists of chemicals used in the C-A facilities including the manufacturer's Material Safety Data Sheets are maintained in accordance with the BNL Chemical Management System. Required reviews of the conventional safety aspects of the C-A facilities shows that use of these chemicals does not warrant special controls other than appropriate signs, procedures, appropriate use of personal protective equipment, and hazard communication training, all of which have been implemented. Reviews are carried out before work begins, via the work planning process.

With regard to environmental impacts, the effluent hazards include generation of ^{3}H and ^{22}Na in the earth shielding, which could potentially contaminate the ground water, and generation of short-lived radioactive gases in the air in the accelerator rings, transfer lines, tunnels and target caves/rooms. Both of these are addressed in this Chapter of the report, and these hazards have been eliminated or controlled by design. When required or at the discretion of management as a best management practice, Suffolk County Article 12 Code is followed in the design of cooling water systems and piping that contain tritium, sodium and other radionuclides. Diversion of radioactive liquid effluent from the sanitary waste system to a hold-up system, or hold up of radioactive liquid in C-A facility sumps, occurs in order to allow retention and sampling before disposal. Air emissions from C-AD facilities are negligible since the potential activation products are sufficiently low; that is, much less than 0.1 mrem/year to the public, to assure doses are ALARA. Results of environmental monitoring and details on exposure pathway analysis are found in the annual BNL Site Environmental Report produced by the BNL Environmental and Waste Management Services Division.

4.5.2. Radiation Hazards

The BNL accelerators and experimental beam lines have been in operation for over 45 years providing protons and polarized protons for the high-energy physics program, and in addition, for the past 15 years, the accelerators have been providing heavy ions for the nuclear physics and NASA programs. Among the three operating modes of the AGS, high flux unpolarized proton beam, polarized proton beam and heavy ion beams, the high flux unpolarized proton operation represents the greatest ionizing radiation hazard because it provides the highest intensity beam. Beam fault calculations for shielding and activation are based on fluxes associated with unpolarized protons. For radiation dose calculation purposes, each nucleon in a heavy-ion nucleus, either proton or neutron, is treated as an independent high-energy particle.

There is a great diversity in the type and energy in the ion beams used at the C-AD facilities. The primary beam is only present when the machines are operating. Before interacting, the accelerated beam is essentially monoenergetic, consisting of only one particle type. Passage through the accelerator equipment, experimental equipment or thin shielding leads to the development of electromagnetic and hadronic cascades, which produce many particle types, distributed over a wide range of energies. As the beam energy increases, a greater diversity of secondary particles exists in the primary area radiation fields. Inelastic spallation reactions become significant at energies above ~1 to 3 GeV. Accelerated and/or circulating beam losses occur as the beam changes direction, during beam injection into and beam extraction from a machine, at collimators and when the beam passes through transition energy in the AGS and RHIC. As these losses occur when the machine is operating, the problems of radiation protection outside the shielding are dominated by photons, neutrons, and for primary energies greater than ~10 GeV, muons.

Typically during high intensity proton operations, the neutron dose to C-AD staff is less than 10% of their total annual dose. Experimenters and operating personnel who are near the shielding during machine operations receive the higher neutron doses. Heavy ion beam operations do not result in neutron dose to personnel.

The primary ion beams, secondary pions and neutron beams, and scattered particles induce radioactivity in the machine components, targets, collimators, beam scrappers and dumps, shielding including soil, cooling water and nearby equipment. The interaction of the hadronic beam with these components produces an inelastic cascade. The particles produced in the materials during the spallation are followed by the evaporation of nucleons from the excited residual nuclei. The full spectrum of isotopes from the original target material nucleus down to tritium may be produced, but in practice only a small number of products are important because of the production cross-section values and radioactive half-life values. This volumetric activation within solid materials requires radiation surveys and radiation controls during entry into these areas following machine shutdown for inspection, maintenance or repair activities. The residual radioactivity produced in cooling water is minimized by passing the water through filters and deionizers, which reduces most activation products except for tritium. With the exception of targets, collimators, beam dumps and scrappers, or machine injection and extraction components, the specific activity is not high. Because of the significantly longer mean free path between interactions, the extent of the activity is widespread, dilute and dispersed; unlike activated materials at reactor facilities. This fact greatly reduces the potential for significant contamination issues at C-A facilities.

Muons arise from the decay of pions and kaons, either in secondary particle beams or in the cascades produced by high-energy hadrons. Muons are weakly acting leptons that deposit energy in materials by electroweak interactions, or ionization with atomic electrons and can only be removed by ranging them out. For example, at 30 GeV, the muon range is ~80 m in soil, ~60 m in concrete and ~20 m in iron. They can have an energy spectrum that varies up to the energy of the parent pions. Thus, shielding design for muons completely dominates the forward shielding requirements. Muon dose is measured by use of standard health physics instrumentation, because they are similar to electrons in every respect, including quality factor, except for their heavier mass.

The principal radiation hazards at C-AD facilities derive from the primary beam flux and duty cycle of the machine. Listed in order of importance, these hazards include:

- inadvertent exposure of workers to primary beam
- exposure to prompt secondary radiation created by primary beam losses during normal operation or episodes of abnormal losses, including areas near labyrinths and penetrations
- exposure to residual radiation induced in machine components such as beam scrappers, beam dumps, collimators, extraction magnets, targets, etc
- inadvertent release of activated cooling water to the environment
- inadvertent release of radioactive contamination to groundwater by allowing rainwater to leach through activated soil shields
- exposure to activated air from primary and secondary beam
- sky shine

4.5.3. Source Terms and Calculated Radiation Fields

In estimating the degree of radiation risk, the shielding is designed assuming the routine and maximum operating beam for the each accelerator and experimental facility. The shield is designed to mitigate the greatest radiation hazards, which are unpolarized protons. Thus, the shield is more than adequate for protection against polarized proton or heavy ion loss because their intensity and/or individual nucleon energies are much less by comparison.

A baseline evaluation of radiation hazards associated with operation and construction of the accelerator and experimental facilities is included as Appendix 2. Specifically, estimates of the following hazards are given here:

- exposure to primary beam
- prompt radiation immediately outside the primary beam shielding
- exposure to residual activity
- activated cooling water
- potential contamination of groundwater from activated soil
- air activation
- sky shine

Details for each facility are given in the following sections. It should be noted that the computed dose rates given in the following sections for each accelerator and experimental facility are conservative and actual dose rates found during facility operations are well below these estimates. The calculations are documented below and in each of the original SADs to show the process that is followed in commissioning a facility. Conservative dose estimates are made to determine the shielding, soil capping, radiological posting, access controls and air emission monitoring requirements during the design phase of a project or facility modification. Post construction/modification beam fault studies are conducted as appropriate to ensure that the designs are adequate. Records of these studies are maintained. Finally, during accelerator and experiment operations at full intensity the following monitoring assures that the facilities are operated within their approved safety basis:

- periodic dose rate checks are made and documented during beam operations to assure that the shielding integrity is maintained
- groundwater samples are obtained at intervals defined by the BNL SBMS and periodic soil samples are taken at known beam loss locations to assure that groundwater is not contaminated and beam losses are not excessive
- periodic confirmatory air samples are obtained to verify that air emissions remain well below 0.1 mrem per year

4.5.3.1. Primary Beam

Primary beam is the ion beam that has not yet interacted with materials and which can cause a whole body dose equivalent rate of more than 50 rem/hr, up to lethal dose. The access controls systems, ACS and PASS, prevent exposure of personnel to primary beam. For direct exposure to the primary beam particles, the only distinction between protons and heavy ions concerns the total mass stopping power and quality factor. Direct exposure is an event against which the maximum level of security is provided in the primary beam areas of C-A facilities. Safeguards against these conditions are provided in accordance with the C-A criteria for monitoring and interlocking of radiation areas. These criteria are specified in Table 3.2.2.1. To simplify safety analyses, in many instances the heavy ions are treated as an independent assembly of nucleons with a beam flux equal to the particle flux times the atomic mass number.

The RF cavities located in the vicinity of the 4 o'clock Collider region produce x-rays as a result of normal operation due to conditioning and multipacktoring. This area has the highest RF hazard compared to other C-A RF areas and thus bound the potential dose to an individual. At full power, dose rates based on measurements during engineering tests of the Proof of Principal (PoP) Collider acceleration cavity and storage cavity are expected to be in the range of 25-200 rad/hr at 1 foot from the cavity[2]. The power supplies for the cavities are interlocked to the PASS system, with the capability of stand-alone running when the Collider is not in operation. Sectionalizing gates inside the Collider Tunnel prohibit access to the cavities by personnel, when the adjacent tunnel is in an access permitted state to secure the cavity area for operation. Operation of the RF cavities does not cause x-ray radiation outside the Collider shielding.

The probability of unsafe failure of the access controls system that would allow an overexposure from primary beam or RF produced x-rays is so low[3] that this hazard is not credible and further analysis is not performed.

4.5.3.2. Prompt Secondary Radiation in Areas Outside Primary Beam Shielding

In estimating the degree of radiation risk, shielding design assumes the routine and maximum operating beam for each portion of the facility. The shield is designed to mitigate the

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[2] S. Musolino, Measurements of Prompt Radiation from the PoP RF Cavity Test Stand in Building 1005 Highbay, August 8, 1995. S. Musolino, Measurements of Prompt Radiation from the Storage RF Cavity Test 4 o'clock Service Building, August 8, 1995.

[3] D. Beavis, Failures in the PLC Based Radiation Safety Systems, October 31, 2000. D. Beavis, Frequency of Interlock Testing, November 6, 2000. D. Beavis, Estimation of Time to Loss of Protection-The D-Downstream Gate, November 13, 2000.

greatest radiation hazards, which are unpolarized protons. Thus, the shield is more than adequate for protection against polarized proton or heavy ion loss because their intensity and/or individual nucleon energies are much less by comparison.

Radiation levels from routine loss of flux have been estimated for locations around the C-A complex using Monte Carlo codes or simple analytical formulas by Sullivan or Tesch. The Sullivan formulas are summarized below. Monte Carlo codes approach the solution as a succession of individual processes rather than in terms of global physical quantities. Making a mathematical experiment that is equivalent to the real physical situation simulates the cascade. Particles in the cascade are tracked from interaction to interaction. The events may be, for example, elastic or Coulomb scattering events, inelastic nuclear events in which any variety of secondary particle may be produced, absorption followed by decay, etc. The processes and particle production are randomly selected using appropriate probability distributions, which are either known or well approximated. At any point in the Monte Carlo simulation, any required macroscopic physical quantity may be scored (i.e., energy, fluence, absorbed dose, stars, etc.). When a sufficient history of events has been obtained, the expected value of each parameter may be obtained to the required statistical accuracy. For many areas, which have been studied extensively with beam faulted in a controlled fashion, results are reported directly.

For high energy particles, 1 GeV or greater, the following analytical formulas may be used for transverse shielding[4]:

$$H = 1.8 \times 10^{-5}\, S_P\, E_0^{0.76}\, e^{-\Sigma\zeta} / (R^2\, (\theta + 35/\sqrt{E_o})^2)$$

[4] A. H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology Publishing, Ashford, Kent, England, 1992. Section 2.1.

for a point source, and

$$H = 2.7 \times 10^{-5}\, S_L\, E_0^{0.76}\, e^{-\Sigma(\zeta/0.94)} / (R\,(\theta + 35/\sqrt{E_o})^2)$$

for a line source.

In these equations, the symbols mean:

H = lateral dose equivalent, mrem

E_0 = primary proton energy, GeV

S_P = number of protons lost at a point, p

S_L = number of protons lost per unit length, p/m

$\zeta = d/\lambda$

d= shield thickness, g/cm^2

λ = high energy attenuation mean free path for shield material, g/cm^2 (Table 1.3 of Sullivan text[5])

R = transverse distance from beam loss to dose point, m

θ= angle from loss to dose point, degrees (90° is assumed based upon facility experience during fault studies)

For high energy particles, less than 1 GeV, the following analytical formulas may be used for transverse shielding[6]:

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[5] Iron is transparent to low energy neutrons and a value of 200 g/cm is used for computations involving a pure iron shield.

[6] A. H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology Publishing, Ashford, Kent, England, 1992. Section 2.2.

$$H = 2 \times 10^{-5}\ S_P\ E_0^{0.76}\ e^{-\Sigma\eta}\ (1 - e^{-m}) / (R^2\ (\theta + 40/\sqrt{E_o})^2)$$

for a point source, and

$$H = 3 \times 10^{-5}\ S_L\ E_0^{0.76}\ e^{-\Sigma(\eta/0.94)}\ (1 - e^{-m}) / (R\ (\theta + 40/\sqrt{E_o})^2)$$

for a line source.

In these equations, the symbols mean:

H = lateral dose equivalent, mrem

E_0 = primary proton energy, GeV

S_P = number of protons lost at a point, p

S_L = number of protons lost per unit length, p/m

$\eta = d/(\lambda(1 - 0.8\ e^{-k}))$, where $k = 3\ E_0$ (correction for variation of high energy λ at < 1 GeV)

d= shield thickness, g/cm^2

λ = high energy attenuation mean free path for shield material, g/cm^2 (Table 1.3 of Sullivan text)

$m = 3.6\ E_0^{1.6}$ (exponent used in the $(1 - e^{-m})$ term, which corrects for the fact that, when < 1 GeV, some of the incident protons will range out in the target material from ionization events before experiencing an inelastic interaction)

R = transverse distance from beam loss to dose point, m

θ= angle from loss to dose point, degrees (90˚ is assumed based upon facility experience during fault studies)

Linac

For the Linac, the source term is a continuous proton loss during operation of 0.1% of the total beam uniformly distributed as a line source from 10 MeV to 200 MeV along the Linac centerline. The ASE Safety Limit for protons is 9 x 10^{17} Gev-nucleons/h or 1.25 x 10^{15} protons/s at 200 MeV. The present ion source configuration limits the actual Linac output to 33 to 35 mA per pulse with a ~500 μsec pulse width and a ~6 Hz beam repetition rate (6.4 x 10^{14} protons/s). The distance involved is ~135 meters so there may be a line source of 4.7 x 10^{9} protons/m/s with the 0.1% loss rate. The earth fill over the 200 MeV proton transfer line to the Booster, the LtB, is 5.4 m, with a transverse rise over run of 1 to 3 for the berm. Thus, the shield thickness at ground level is 16.2 m. The Linac enclosure itself provides 0.61 m of concrete thickness overhead and on the sides at the 200 MeV end. At the low energy end, 10 MeV, the thickness of the overlying earth is 3 m, and the wall and roof of the Linac enclosure is 0.52 m. The earth shield and concrete enclosure thickness increases as proton energy increases along the length of the Linac. At the end of the Linac tunnel, the 200 MeV proton beam splits to provide a maximum allowable flux of 1 x 10^{14} protons/s to Booster or AGS with the remaining flux transported to BLIP.

In addition to the Linac to Booster line (LtB) the Linac may inject directly into the AGS through transport along the High Energy Beam Tunnel (HEBT). This path is currently not available but is included in the discussion because it was used in the past and may be used again in the future. The earth shield over HEBT is 3 m thick with a transverse rise over run of 1 to 2, thus the shield thickness at ground level is 6 m. The area outside the HEBT is a locked and fenced enclosure, posted as a Radiation Area during Linac running. This protects personnel from a potential beam fault dose equivalent rate of about 20 mrem/hr.

The penetrations in the Linac include the tank 1 gate or tunnel entrance, many 40 cm transmission line holes, many 60 cm vacuum lines, many 60 cm cable trays, many 15 cm cable sleeves, and two bricked-up 1.8 m x 2.4 m access ports for equipment. The transmission line, cable trays, cable sleeves and vacuum penetrations do not give direct line of sight to the tanks, which contain the beam. The walkways in Building 930 along side the Linac are posted to control exposure to radiation.

The penetrations in HEBT include a plug door, many 15 cm cable sleeves, two 60 cm cable trays, one 30 cm cable opening, the LtB - Booster penetration, the TtB – Booster penetration, the AGS - HEBT door and labyrinth, a 60 cm x 120 cm airshaft, and two 7 cm cable penetrations. The cable penetrations and the airshaft do not give direct line of sight to the beam line.

The maximum credible unplanned loss is complete loss of the beam at any single point at the maximum energy for a short period. This is termed a "fault" condition throughout the text of this report. In appropriate areas, fault levels are detectable by radiation monitors essentially instantaneously, and if interlocked, the beam will shut down within a maximum of 9 seconds[7]. For areas where a fault may produce more than 20 mrem per fault, a system of access controls such as barriers and locked fences are used and the area is upgraded to one of several types of radiation controlled areas as defined in the Table 3.2.2.1.

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[7] G. Bennett to D. Beavis, RSC Chairman, "Chipmunk Response Time," BNL Memorandum, October 9, 1991.

Table 4.5.3.a Summary of Routine and Faulted Beam Loss and Radiation Levels for Linac (200 MeV Protons)

Shield Type or Loss Point (2 m air assumed in addition to the shielding)	Area of Interest	Routine Dose Equivalent Rate (0.1% loss rate or 4.7 x 10^9 p/s-m) mrem/h	Fault Dose Equivalent[8] per Linac Pulse (6.4 x 10^{14} p/s; ~6 Hz) mrem/pulse (mrem/h)
Calculation:			
0.6 m concrete, 5.4 m earth	Linac Tunnel Top	1.1 x 10^{-7}	2 x 10^{-7} (0.005)
0.6 m concrete, 3 m earth	HEBT Top	5.4 x 10^{-4}	8.3 x 10^{-4} (20)
0.6 m concrete, 6 m earth	HEBT Side	1.4 x 10^{-8}	2.5 x 10^{-8} (0.001)
1.2 m concrete, 3.3 m earth	Linac Equipment Bay	1.2 x 10^{-5}	2 x 10^{-5} (0.5)
Fault Studies[9]			
Outside on Berm:			
Beam at HEBT Stops	HEBT Top	-	1.3 x 10^{-3} (30)
Beam at HEBT Stops	Blip Pump House Gate	-	2.7 x 10^{-3} (60)
Beam at HEBT Stops	In BLIP Pump House	-	5 x 10^{-2} (1060)
Beam at HEBT Stops	AGS / HEBT Gate	-	2.4 x 10^{-1} (5180)
Inside Enclosures:			
Beam Near TtB Penetration	HTB Enclosure[10]	-	1.2 x 10^{-2} (260)
Beam Near LtB Penetration	Booster Enclosure	-	2.6 x 10^{-3} (55)
Beam Near HTB Penetration	Booster Enclosure	-	7 x 10^{-3} (150)

The original 750 KeV Cockcroft-Walton described by Wheeler and Moore in "Shielding of the 200 MeV Linac," AGSCD-10, was replaced by a more reliable, low maintenance 750 KeV

[8] In appropriate areas, fault levels are detectable by radiation monitors instantaneously, and if interlocked, the beam will shut down within 9 seconds. It is estimated that 54 full energy beam spills may occur within this 9-second interval at a design repetition rate of 6 Hz. For areas where a fault may produce more than 20 mrem per fault, a system of access controls such as barriers and locked fences are used and the area is upgraded to one of the several types of radiation controlled areas as defined in the BNL Radiation Control Manual.
[9] D. Beavis, Summary of Linac Fault Studies 1 – 3, HTB Safety Analysis Report, Appendix 7.7 (September 1991).
[10] Small area source that is less than 1000 cm^3.

Radio Frequency Quadrupole (RFQ) in December 1988. This preinjector is equipped with a rotationally symmetric magnetron source, fast beam diagnostics, and a fast beam chopper, which removes undesirable beam between Booster bunches that are otherwise dumped in the Booster Ring. The fast beam chopper removes H^- particles at 750 KeV, particles that would otherwise be lost at Booster energies.

The 35 KeV transport line is 1.2 m long and it leads into the RFQ. The RFQ is 1.6 m long and experience indicates 85% transmission of the beam at the exit of the RFQ. The output of the RFQ is ~ 80 mA with a design output up to 100 mA. The RFQ currently operates at a ~6 Hz repetition rate (design of 10 Hz), and the beam pulse width is variable depending upon the needs of the AGS (~0.5 ms). From the exit of the RFQ, the beam is transported to the Linac entrance with loss occurring in the aperture of the first beam buncher at an energy of 750 KeV. Eighty to 85% of the beam at the Linac entrance is captured and accelerated to 200 MeV. The current configuration allows the Linac to operate with an output pulse up to 33 to 35 mA (6.4×10^{14} p/s), although the capability is there to reach higher currents in the future, about 50 mA ($\sim 10^{15}$ p/s), if the ion source is upgraded.

Based on the above performance characteristics, about 8.5×10^{13} p/s are lost in the accelerating cavities of the Linac. Most of this loss is in the first cavity, which accelerates protons to 10 MeV. The lost protons stop on the copper surfaces of the drift tubes and produce x-rays and small amounts of low energy neutrons.

Loss of protons with energies above 50 MeV in the Linac, LtB or HEBT regions produces neutrons that may reach nearby facilities. The earth shield in the Linac area rises proportionately with proton energy, up to 5.4 m when the protons reach 200 MeV. Following the Linac accelerating cavities is the LtB line that is located in the first 15 m of HEBT. Linac beam may be transported into the Booster or directly into the AGS through the full HEBT line, bypassing the Booster. Shielding over the HEBT transport line is 3 m earth and 0.6 m concrete. The mechanisms of beam loss in the Linac, LtB or HEBT are two kinds: 1) loss of longitudinal stability and 2) failure of the magnet system. These failures may give rise to total beam loss that is normally detected after several lost pulses and corrected by the operators. Transient phenomena may give rise to a continuous low-level loss of beam. While a 0.1% uniformly distributed loss is the ideal condition for the Linac, significantly greater losses are acceptable based on the actual thickness of the HEBT shielding and the proximity of other facilities around the Linac.

The limiting continuous loss in HEBT is about 2%. This is based on 25 mrem per year to personnel in the BLIP Facility, which is closest to the HEBT line, and which is occupied about 1000 hours per year. The HEBT line was originally used for direct injection of protons from Linac to AGS. Because the Linac currently injects into the Booster, the HEBT line is only used for test beams for a fraction of the time when the Linac operates. Assuming a distributed loss over HEBT line, a 36 m line source, a flux of 1×10^{14} protons/s to Booster or AGS, a lateral distance between BLIP and HEBT of 15 m, and loss distributed in time over 1000 hours; the line source equation indicates a maximum allowable loss rate of 5.5×10^{10} p/s-m during 1000 hours of operation. This is equivalent to a 2% beam loss continuously during the proton running period. A similar analysis was made for continuous loss in the LtB.

Fault studies (see Table 4.5.3.a) indicate that a point loss calculation for total beam loss in HEBT overestimates the measured dose equivalent rate outside the shield on the top of HEBT. This may be due to spreading out of the beam during an actual loss, which does not agree with point source geometry used in the calculation, or may be due to not accounting for shielding offered by magnets and beam components. In general, point source calculations are considered bounding, upper estimates since they are difficult, if not impossible, to achieve.

Within the BLIP Pump House are cooling lines containing water activated by primary beam losses in the HEBT beam stop. Very short-lived dissolved radioactive gases are in the water, which give rise to a photon flux in the Pump House that adds to the dose equivalent from neutrons arising from primary beam losses.

The polarized proton beam originates as a negatively ionized vertically polarized hydrogen beam from a polarized ion source. These H- ions are injected into the Linac RFQ. The beam is transported through the Low Energy Beam Transport line (LEBT) into the Linac where it is accelerated to 200 MeV. The beam accelerates from the RFQ with a maximum of a few TP per second reaching 200 MeV. This flux is an order of magnitude less than unpolarized protons.

An x-ray hazard along the length of the Linac rf tanks exists whenever a spark occurs. Exposure rates near the tanks at a level of 1 to 5 R/h have been observed during normal operations. This area is on restricted access during maintenance periods and requires training and a self-reading dosimeter for entry. Even though entry through the Linac Tank 1 gate ensures proton beam is interlocked off, the rf may be reset from inside the gate for testing purposes. In addition to training in the hazards associated with this area, a series of fluorescent lights along the tanks warns personnel that rf radiation is present.

Tandem and TtB

By its very nature, the TVDG facility has a complex and varied capability for producing radiation depending on the type of ion being accelerated. Energies of Tandem accelerated ions are proportional to the charge state achieved by the ions when they undergo stripping within the accelerator tank. Because lighter ions can be stripped to charge states comparable to their atomic numbers, they can achieve a relatively high energy per nucleon and as such are capable of producing appreciable numbers of fast neutrons and associated gamma-rays when they strike a target. Heavier ions cannot be stripped to charge states comparable to their atomic number so they can only attain a relatively low energy per nucleon. Such particles do not produce nuclear reactions when striking a target, and thus do not produce an appreciable radiation field. As a result of this diverse capability for producing radiation, a very diverse access controls system is in place. Studies have shown that adequate controls are in place.[11]

The TtB shield and the TtB beam current monitoring device are designed to mitigate the greatest radiation hazards, which exist when running with low-mass ions. The shield alone is more than adequate for protection against high-mass heavy-ion losses because heavy-ion beam intensity and/or individual nucleon energies are much less by comparison.

After examining the experimental needs at RHIC, it was determined that the annual, total number of deuterons would need to be about $7x10^{17}$. This accounts for normal beam losses and deuteron beam tuning in Tandem, TtB, Booster, AGS and AtR.

When the TtB line is delivering beam to downstream users, a 10% beam loss has been observed. No specific points of chronic loss have been identified, and the distribution of these losses is not known. When the TtB line itself is being tuned, beam loss is inherent in the tuning process as wire chambers and Faraday cups are inserted at various places in the line. Adding these losses gives a total loss estimate at a single point of about $2x10^{16}$ deuterons per year. The

[11] J. Benjamin, C. Carlson, J. Throwe and F. Zafonte, Building 901A Shielding Effectiveness Studies, 7/92 and 4/94, Tandem Van de Graaff Facility, August 1994. This is Appendix XI of the TVDG SAD dated June 1995.

maximum incremental loss at a single point was estimated to be about 4.5×10^{13} deuterons in one hour.

The normal running current in the TVDG accelerator room was initially planned to be 67 nA of deuteron beam at 12 MeV. The normal terminal voltage was planned to be 6 MV. For a full-energy beam fault, radiation levels from deuterons could fault to about 50 rem/h at one foot at 0^o from a 30 MeV deuteron beam that would result from a voltage fault of 15 MV. For a full-intensity beam fault, the radiation level could fault to a few hundred rem/h at 1 foot at 0^o if the current is intentionally tuned to maximum 10 μA. Thus, dual redundant interlocks are required in the TVDG accelerator room for deuteron operations. It is noted these fault conditions require two events: an intensity or voltage fault and stopping the beam at a single point. These radiation levels are summarized below in Table 4.5.3.b.

Table 4.5.3.b Calculated Radiation Levels in the TVDG Accelerator Room and the TtB (Deuterons)

Loss Description	Deuteron Current	Terminal Voltage	Instantaneous Dose Equivalent at 1 foot at 0°, rem/h
TVDG Normal Beam, Point Loss (single fault)	67 nA	6 MV	1.5
TVDG Full Energy Beam, Point Loss (double fault*)	67 nA	15 MV	50
TVDG Full Current Beam, Point Loss (double fault*)	10,000 nA	6 MV	230
TtB Normal Beam, Anticipated Beam Loss (routine loss)	6.7 nA or 10% in transit to RHIC ($4.5x10^{13}$ deuterons for one hour at a point)	6 MV 6 MV	0.15 0.04
TtB Normal Beam, Point Loss (single fault)	67 nA	6 MV	1.5
TtB Full Current Beam, Point Loss (double fault)	200 nA	6 MV	4.5

* Double fault - intensity or voltage fault coupled with stopping the beam at a single point.

The actual parameter limits for the FY 03 d-Au run as authorized by the RSC at RHIC were eventually increased to 18 MeV deuterons[12], a 200 nA interlock and an alarm at 80 nA. These conditions are well bounded by the double fault condition analyzed above.

[12] K. Yip, Increased Neutron Dose Due to Increased Deuteron Energy in the TTB Line, December 15, 2002.

Booster

Among the three operating modes of the Booster, which are high flux unpolarized proton beam, polarized proton beam, and heavy ion beams, the high flux unpolarized proton operation represents the greatest ionizing radiation hazard. With the exception of the shielding over the first dipole following the stripper for heavy ions, all calculations for shielding and activation are based on fluxes associated with unpolarized protons.

Table 4.5.3.c Summary of Booster Beam Flux and Beam Loss

Parameter	Unpolarized A = 1	Polarized A = 1	Sulfur A = 32	Gold A = 197
Beam Flux (sec^{-1})	1×10^{14}	1.5×10^{12}	1.5×10^{10} ions	3.2×10^{9} ions
Injection Loss (sec^{-1})	1×10^{13}	3×10^{11}	3×10^{8} ions	6×10^{7} ions
Injection Energy (MeV/nucleon)	200	200	4.688	1.066
Acceleration Losses (sec^{-1})	6×10^{11}	1.5×10^{10}	1.5×10^{8} ions	3.2×10^{7} ions
Extraction Losses (sec^{-1})	2×10^{13}	1.5×10^{10}	1.5×10^{8} ions	3.2×10^{7} ions
Stripper Losses	NA	NA	1.5×10^{9} ions	1.6×10^{9} ions
Extraction Energy (GeV/nucleon)	1.5 to 2.2	1.5 to 2.2	0.967	0.35
Maximum Credible Loss at Extraction Energy	1×10^{14}	1.5×10^{12}	1.5×10^{10} ions	3.2×10^{9} ions

For a planned beam loss, the assumption is 50% of the loss occurs at a single point such as the dump/catcher and the remainder uniformly distributes around the Booster Ring. For extraction loss, 80% of the loss is on the septum and 20% is on the first dipole downstream. The maximum credible unplanned loss is complete loss of the beam at any single point at the maximum energy for a short period of time. Generally, the only distinction between protons and heavy ions concerns the total mass stopping power from direct exposure to the primary beam particles. This is an event against which the maximum level of security is provided in the primary beam areas of the Booster. In all other instances, the heavy ions are treated as an independent assembly of nucleons with a beam flux equal to the particle flux times the atomic mass number. Safeguards against all loss conditions are provided in accordance with the C-A criteria for monitoring and interlocking of radiation areas.

The shielding of the tunnel enclosure and the interfaces to the 200 MeV proton Linac and the AGS have been analyzed by Gollon[13], Casey[14] and Lessard[15]. Sufficient shielding is provided to ensure that radiation levels in all areas for normal operating conditions meet BNL and DOE criteria. Fault conditions were analyzed to ensure that unacceptable radiation levels are controlled. The types of warning/control systems are consistent with the existing C-A area classifications.

A summary of the results is presented in the following tables with details given in the following text. These computed values are upper limits because it is not possible to lose the

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[13] P. J. Gollon, Booster Tunnel Shield Calculation, Booster Technical Note #66, October 24, 1986, in AGS Booster Project Preliminary Safety Analysis Report, Appendix 7.1, Brookhaven National Laboratory, Upton New York, 11973, December 1, 1987.

[14] W. R. Casey, Additional Booster Shielding Calculations, Booster Technical Note #93. September 28, 1987 in AGS Booster Project Preliminary Safety Analysis Report, Appendix 7.2, Brookhaven National Laboratory, Upton New York, 11973, December 1, 1987.

[15] E. T. Lessard, Booster Shield Wall/Door Analysis, March 30, 1989.

beam at a single point. It is noted that the current Booster design limits the extraction energy to ~2 GeV, however 2.2.GeV was conservatively used to bound the computed doses.

Table 4.5.3.d Summary of Booster Flux Loss and Radiation Level Summary

Loss Flux Type (particles/s)	Area of Interest	Nucleon Energy	Routine Peak Dose Rate (mrem/h)	Peak Fault Dose Rate[16] (mrem/h) (Maximum Flux)
Injection (1×10^{13})	Booster Tunnel Top	200 MeV	0.0003	30 (4×10^{14})
Injection (1×10^{13})	Booster Tunnel Side	200 MeV	0.00006	0.6 (4×10^{14})
Acceleration (6×10^{11})	Booster Tunnel Top	700 MeV	0.2	2500 (1×10^{14})
Acceleration (6×10^{11})	Booster Tunnel Side	700 MeV	0.04	150 (1×10^{14})
Fault (1×10^{14})	Booster Tunnel Top	2.2 GeV	NA	6800
Fault (1×10^{14})	Booster Tunnel Side	2.2 GeV	NA	450
Extraction (2×10^{13})	B914 Roof Over Septum	2.2 GeV	300	1650 (1×10^{14})
Extraction (1×10^{14})	Remaining B914 Roof	2.2 GeV	3	205,000
Studies (1.5×10^{13})	Booster Tunnel Over Dump	2.2 GeV	20	130 (1×10^{14})
Studies (1.5×10^{13})	Fence Near Dump	2.2 GeV	0.3	2 (1×10^{14})
Fault (1×10^{14})	AGS from Booster	2.2 GeV	NA	750
Fault (1×10^{14})	AGS Labyrinth. Door from Booster	2.2 GeV	NA	1350
Fault (4×10^{14})	Booster from Linac	200 MeV	NA	240
Fault (1.3×10^{13})	Booster from AGS	28 GeV	NA	1400
Fault (1.3×10^{13})	Booster Labyrinth. Door from AGS	28 GeV	NA	2500
Extraction (1.6×10^{9}) - Gold	B914 Roof Over Stripper	1.066 GeV	5	10 (3.2×10^{9})
Extraction (6×10^{11})	B914 Plug Door	2.2 GeV	2.7	680 (1×10^{14})
Extraction (6×10^{11})	B914 Man-Gate	2.2 GeV	0.7	160 (1×10^{14})
Extraction (6×10^{11})	B914 North Entrance	2.2 GeV	0.3	70 (1×10^{14})

[16] Fault levels are detectable by radiation monitors after one pulse. When the fault is detected and stopped after one second, the accidental dose to an individual in unfenced areas is well below the design guideline of 20 mrem.

Injection losses are estimated at 10% ($1x10^{13}$ p/s) at 200 MeV. Assuming that all of these losses occur at a single point, the dump/catcher, a peak radiation level of 0.3 µrem/h is produced at the top of the berm and less than 0.06 µrem/h horizontally. The dump/catcher is shielded internally with one meter of heavy concrete equivalent and externally with 5.5 m of sand. The Booster Ring is shielded less, 4.6 m of sand vertically and 6.1 m horizontally, when compared to the dump area and the fault flux for 200 MeV protons $4x10^{14}$ p/s. Therefore, away from the dump area, a fault level of 30 mrem/h at the berm top and 0.6 mrem/h at the berm side is possible with injection energy protons for a short period of time.

Planned losses during acceleration are 1% or less and occur with an average energy of 700 MeV. Assuming all of these are lost at a point, which is the dump/catcher, peak radiation levels are 0.2 mrem/h at the top of the berm and 0.04 mrem/h at the side of the berm. If a point loss during acceleration occurred at full beam flux, 1×10^{14} p/s, the berm top would peak at 2500 mrem/h, and the berm side at 150 mrem/h. Fault losses are typically not at a point and distribute over 10 m or more at these momenta. Radiation levels decrease by a factor of two for a loss spread over 10 m, and by a factor of 30 if losses are spread uniformly around the entire Booster Ring.

Faults at 100% of the beam at 2.2 GeV at a point for a short period of time result in up to 6.8 rem/h at the berm top and 450 mrem/h horizontally. Due to these potential levels, the berm is posted in accordance with the requirements of the BNL Radiological Control Manual and is enclosed by a fence. Access is limited to authorized individuals only.

Losses at extraction are about 30% and occur at an energy of 2.2 GeV. All of these losses are assumed to occur on the extraction septum (80%) and the first dipole magnet (20%) following the septum inside Building 914. Building 914 was constructed from the decommissioned 50 MeV Linac and has a structural limitation of 1.8 m of soil overhead. Sixty centimeters of iron rising to 2.3 m in the forward direction where space permits reduces the routine exterior radiation level on top Building 914 to about 300 mrem/h, which occurs over a 40 m^2 area. Most of the remaining Building 914 roof is about 3 mrem/h for routine extraction loss conditions.

Since the internal iron shield does not fully enclose the transfer line between the Booster and the AGS, momentary peak levels of 57 mrem/s are possible under full fault conditions at 7.5 Hz or $1x10^{14}$ p/s. For this reason, the roof area above Building 914 is fenced and secured as a Class III area with possible faults into Class II, and the access gate configured with a hard-wired switchgear type relay that interlocks the beam. In addition, redundant radiation monitors are used in this region to interlock the beam and limit the duration of the fault. Based on experience at the AGS, fault levels are detectable by radiation monitors after one pulse. If $1x10^{14}$ p/s stop in the region not enclosed by iron, about 57 mrem in one second occurs within the fenced-in region on top of Building 914. If the fault is detected and stopped after one second, the accidental dose to a person would be much less than the design guideline of 20 mrem since the nearest uncontrolled area is 50 feet away.

The first dipole past the heavy ion stripper, which is in the transfer line between the Booster and AGS, requires overlying shielding. Projected energy losses are $1x10^{11}$ GeV/s for Au ions. Poorly stripped ions are swept out at the first dipole after the stripper. A local iron shield 36 cm thick is installed to reduce exterior levels to less than 5 mrem/h on the roof of Building 914. Fault levels are 10 mrem/h.

During Booster studies, the beam dump can receive the full Booster beam. Studies are normally conducted at a peak flux of 1.5×10^{13} p/s at 1.5 GeV but 2.2 GeV is assumed, and studies do not occur more than about 500 h/y. The thickness of the steel dump and the iron shield surrounding it contribute an additional equivalence of 1 m of heavy concrete. The sand berm over the dump is 5.5 m thick and this thickness extends 15 m horizontally from the dump. The external radiation levels over the top of the berm are 20 mrem for one hour of studies and about 0.3 mrem in one hour at the berm fence. Fault levels are about six times these planned levels.

At Building 914, routine occupancy near the inhabitable side of the shield wall or man-gate opening would not occur. Because of possible fault levels of 300 mrem/h for a short period, the inhabitable portion of Building 914 is designated as a Radiation Area, and an alarmed/interlocked radiation monitor is installed. The entrance to Building 914 is 27 m from the shield wall and man-gate. The routine dose rate at the North Entrance is less than 0.01 mrem/h. Routinely, the highest levels are near the shield wall and man-gate entrance and they are 0.1 mrem/h. These estimates are based on a septum that is unshielded along its side and a 30% flux loss. In fact, the septum has a light-concrete photon shield along side it in order to reduce the residual radiation when passing by or working nearby that would also act as a shield during operations.

At least 2.4 m of concrete shielding is placed at the interface between the Booster tunnel and the 200 MeV high-energy beam transport (HEBT) tunnel of the Linac. The radiation at the Booster side of the interface shield is less than 0.4 mrem/h assuming a planned loss of less than 1% in the Linac HEBT. A fault loss of the maximum Linac beam (~35 mA) at a point in the HEBT line near the interface to the Booster results in 240 mrem/h in the Booster tunnel. Such losses would be detected by the Linac radiation monitoring system, which would automatically turn the beam off.

Multiple redundant lockout of bending magnets in the Linac/Booster transfer line inhibit the direct transfer of Linac beam into the Booster tunnel, unless the Booster tunnel is clear of personnel and secure for normal operation.

Certain special areas, where the side shield is thinner than usual because of space restrictions, such as in the interface of the Booster with the Linac building and Building 914, have concrete or steel inserts in order to assure at least 6 m of equivalent earth. This keeps levels under normal conditions to less than 0.3 mrem/h.

The side shielding at the interface between the Booster and the AGS, which is the equivalent of 6 m of earth side shielding, is designed so that the two machines can operate independently of each other while the other tunnel is opened for maintenance. This criterion is necessary because the Booster may operate with one type of particle beam (e.g. heavy ions for NASA experiments at NSRL), while the AGS is engaged in physics operation with direct injection of another particle beam. Under these conditions, independent access is required. There is a labyrinth passage, joining the AGS and the Booster Rings, with High Hazard Radiation Area security doors at each end. 0pening these doors crashes the machines. During Booster operation while the AGS tunnel is open, interlocks on the beam transfer dipole in the Booster extraction channel inhibit the transfer of primary beam to the AGS. The worst credible accident, loss of the Booster beam at the Building 914 wall near the AGS, causes levels in the AGS tunnel to rise to 750 mrem/h for 1 to 2 seconds. The reverse case is operation of the AGS while the Booster tunnel is open for maintenance. The reverse case, which had been possible in the past cannot occur under the current configuration, is included should it be used in the future. For operation of the AGS at a maximum beam flux of 2×10^{13} protons per pulse at 1.5-second repetition rate, the worst case of total beam loss causes 1400 mrem/h in Building 914 for approximately 1 to 2 seconds. Radiation monitors interlocked to each machines operation are provided.

Transmission from losses in the AGS through the AGS-Booster labyrinth is measured at 4×10^{-5}. Calculations indicate that transmission through the labyrinth is from 8×10^{-6} to 4×10^{-7} for a loss at the mouth of the labyrinth. The measured transmission cannot be directly compared to calculations since losses occurred near the mouth and along the sidewall of the labyrinth in the AGS Ring. Using the measured transmission, the worst-case level is 2500 mrem/h. The reverse, which is the worst-case level at the AGS door to the labyrinth from a loss in the Booster, is 1000 mrem/h assuming that the 4×10^{-5} transmission value applies.

NASA Space Radiation Laboratory (NSRL)

A summary of the routine maximum and faulted beam assumptions for NSRL safety analyses are shown in Table 4.5.3.e:

Table 4.5.3.e Summary of Routine, Maximum and Faulted Beam Assumptions for NSRL

Quantity	**Maximum Value**
Annual Energy Flux from Booster SEB	10^{17} GeV in one year
Hourly Energy Flux from Booster SEB	$6x10^{14}$ GeV in one hour
Annual Energy Flux on the NSRL Beam Stop	$3x10^{16}$ GeV in one year
Hourly Energy Flux on the NSRL Beam Stop	$6x10^{14}$ GeV in one hour
Annual Energy Flux on NSRL Targets (0.25 nuclear interaction lengths)	$3x10^{16}$ GeV in one year
Hourly Energy Flux on NSRL Targets (1.0 nuclear interaction length)	$6x10^{14}$ GeV in one hour
Maximum, Single Event, Non-routine Point Loss at any Location[17]	$6.75x10^{15}$ GeV

The prompt radiation at the edge of the berm above the target in the Target Room, which is the point of minimum shield thickness, was computed using the Tesch formula[18] for 3.07 GeV protons. This dose was found to be 2.42×10^{-17} rem per proton. Table 4.5.3.e prescribes a maximum hourly limit of beam interacting on target to be 6×10^{14} GeV, which would result in 4.73 mrem per hour. Averaged over a year, the hourly dose is much less. For a "thick target" the average GeV per hour is 2×10^{13} versus the 6×10^{14} considered above, for a reduction factor of 0.033, or an average dose rate of 0.16 mrem/hr.

[17] The maximum, single-event, non-routine point loss is $1.5x10^{14}$ 5-GeV nucleons/sec for 9 seconds. Nine-seconds is the assumed response time of fixed-area radiation monitors to interlock the beam. Thus, a single-event, high-energy nucleon loss of $6.75x10^{15}$ GeV is the maximum fault assumption for any location at NSRL. It is noted in BNL Memorandum, J. Geller to D. Beavis, RSC Chair, "Time to Chipmunk Interlock for Large Radiation Faults," March 2, 1999 that tests of the internal chipmunk circuitry yield an absolute minimum response time of 0.65 seconds. Nine seconds is taken to include the response time of the external circuitry that includes relays and critical devices.

[18] K. Tesch and H. Dinter, Radiation Protection Dosimetry, Vol. 15 No. 2 pp. 89-107 (1986).

The dose on the berm slope shown next to the beam dump was compared to the dose at 90° with respect to the target on the top berm using the CASIM program for high-energy particle ***cas***cade-***sim***ulations.[19] The result was that the dose on the slope is less than at the berm top. Thus, the hourly dose rates at the top of the berm are bounding, even for the situation where no target is in place.

Upstream of the Target Room the shielding consists of 15 feet of earth. At the edge of the berm here, the Tesch formula gives 4.52×10^{-17} rem per proton. Assuming a 5% inadvertent loss of the maximum hourly limit (3×10^{13} GeV) gives 0.44 mrem/hr. The average hourly dose rate corresponding to a chronic 5% inadvertent loss is a factor of 0.033 less, which is a dose rate of 0.015 mrem/hr. The assumption of a hypothetical 5% loss just before the target is based on experience with the final focusing magnet in a beam line at AGS; however, it is noted that operators monitor losses and are required to reduce beam losses to ALARA levels.

The prompt radiation at the nearest point in the Target Room is estimated by evaluation of the labyrinth connecting the Target Room with the Support Building 958 which is occupied with experimenters during operations of NSRL. The estimate was made using the MCNPX code. The dose at door of the support building assuming 3.07 GeV protons incident on a 12 cm plastic target, which is 0.16 interaction length, is 10^{-18} rem per proton. The maximum hourly dose is obtained by assuming 6×10^{14} GeV on a one interaction length target. It is assumed that neutrons dominate the dose at the support building labyrinth-door. The re-entrant dump design supports this assumption. The resultant maximum dose rate is 0.84 mrem per hour. The average hourly rate assumes a 0.25 interaction length target. Combining this with the average 2×10^{13} GeV per hour gives 0.01 mrem per hour.

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[19] The CASIM code overestimates the dose in the forward direction when compared to the actual condition estimated by improved codes such as MCNPX at the GeV energy scale.

Alternating Gradient Synchrotron (AGS)

In estimating the degree of radiation risk, assumptions about the beam flux and the beam loss are made. They are based on the design of the AGS facility and are indicated in Table 4.5.3.f. The fundamental assumption is that the shield is designed to mitigate the greatest radiation hazard. Thus, a shield designed to specifications for unpolarized proton loss is more than adequate for protection against polarized proton loss or heavy ion loss since their flux and/or individual nucleon energies are much less by comparison. The AGS has been analyzed assuming a maximum beam flux of 1 x 10^{14} unpolarized protons per second.

Table 4.5.3.f Summary of Planned Beam Loss in the AGS Ring

Location and Beam Energy	Spot Loss Near Thick Shield (% of beam flux)	Spot Loss Near Thin Shield (% of beam flux)	Distributed Loss (% of beam flux)
Injection Losses (1.5 – 2.2 GeV)	8	1	1
Transition Losses (7 GeV)	0.9	0.05	0.05
Extraction Losses (27.5 GeV)	0.9	0.05	0.05
Studies Losses (10 GeV)	4.9	0.05	0.05

The above Table assumes that protons are injected into the AGS Ring through the Booster. Direct injection into the AGS is a possibility by transporting beam from the Linac through HEBT. This ability is not possible without modifications but is included in the discussion should it be used in the future. In this mode of operation, injection losses are approximately 60% at 200 MeV based on the measurements reported during the 1986 Slow Extracted Beam run. This lost energy flux at injection, 1.2×10^{13} GeV/s, is the well below the 8% at 1.5 to 2.2 GeV using the Booster. Thus, the injection losses assuming the Booster is operating bound the dose consequences for either mode of operation.

Unpolarized proton losses are more explicitly stated in Table 4.5.3.g, and the location of the loss is indicated by correlating the loss with the amount of overlying shielding. Additional shielding by magnets of 0.42 m of iron pole tip is assumed to attenuate radiations rising in the vertical direction towards the top of the shield. Experience shows that when viewed indirectly through measurements at the outer surface of a thick shield, a point loss in the AGS Ring has a characteristic source length of 16 m for the most localized beam loss.

Table 4.5.3.g Proton Beam Loss and Location in the AGS Ring

Loss Type	Protons Lost per Year	Protons Lost per Meter-Year	Energy (GeV)	Concrete Thickness (m)	Earth and Soilcrete Thickness (m)
Injection[a]	6.6×10^{19}	4.1×10^{18}	1.5 – 2.2	0.3	6.0
Injection[b]	8.2×10^{18}	1.0×10^{16}	1.5 – 2.2	0.3	5.7
Injection[a]	8.2×10^{18}	5.1×10^{17}	1.5 – 2.2	0.3	4.5
Transition[a]	7.4×10^{18}	4.6×10^{17}	7	0.3	6.3
Transition[b]	4.1×10^{17}	5.1×10^{14}	7	0.3	5.7
Transition[a]	4.1×10^{17}	2.5×10^{16}	7	0.3	4.5
Ejection[a]	7.4×10^{18}	4.6×10^{17}	27.5	0.3	6.3
Ejection[b]	4.1×10^{17}	5.1×10^{14}	27.5	0.3	5.7
Ejection[a]	4.1×10^{17}	2.5×10^{16}	27.5	0.3	4.5
Studies[a]	4.2×10^{19}	2.6×10^{18}	10	0.3	6.3
Studies[b]	4.1×10^{17}	5.1×10^{14}	10	0.3	5.7
Studies[a]	4.1×10^{17}	2.5×10^{16}	10	0.3	4.5

a: 16 m spot loss
b: Loss distributed around Ring, 800 m

Essentially, two types of shield exist at the AGS Ring. One is a 6 to 6.9 m thick earth and soil-cement shield which covers the major areas overlying the injection, transition, ejection and studies losses. Another is a 4.5 to 5.1 m thick earth and soil-cement shield which covers the remaining parts of the AGS Ring. The beam height is 3.3 m below the concrete roof of the AGS Ring which is used to support the over lying layers of soil and soil-cement. The specific thicknesses of top shield are listed in Table 4.5.3.h below:

Table 4.5.3.h Thickness of Top Shield

Top of Sector	Shield (meters)
G20 - I13	6.0
I13 - J5	5.1
J5 - K5	6.3
K5 - L10	5.1
L10 - A15	6.0
A15 - B10	6.0
B10 - D10	4.5
D15 - E20	4.5
E20 - F20	6.9

The section F20 through G20 is the AGS target building portion of the Ring, and the shield top thickness is 2.4 m heavy concrete or more, which is 4.7 m earth equivalent or more. The shield thickness for the berm top is not continuous. It is punctuated by penetrations which are: 2 escape hatches, a series of pipes varying in diameter from 20 to 60 cm, 5 fan houses, 4 labyrinths, 2 plug doors, 1 gate, 1 trench, 1 cable run, the north and south wiring tunnels, the FEB tunnel, the north conjunction area, and the target building. Additionally, a roadway crosses the berm top between D10 and D15 and near J10. The shield thickness beneath the roadway is 3 m of earth.

For a planned beam loss, the assumption is that part of the loss occurs at a single place such as the internal dump/catcher at J10, which is shielded by the thicker part of the berm, and the remainder of the loss uniformly distributes around the AGS Ring. Additionally, as viewed from the outside of a shield, a 16 m loss is assumed to occur routinely at any thin part of the Ring shield, rather than a less conservative distributed loss.

A summary of the computed dose equivalent rate results for the AGS is given below in Tables 4.5.3.i and 4.5.3.j. These estimates are overly conservative but show that adequate shielding is in place. Many of the areas have had shielding upgrades that are not reflected in the computed fault doses.

Table 4.5.3.i AGS Flux Loss and Radiation Level Summary

Shield Type	Area of Interest	Operation	Nucleon Energy (GeV)	Routine Dose Equivalent Rate (mrem/h)	Fault Dose Equivalent per AGS Pulse[20] (mrem/pulse)
Thin				0.5	0.02
Thick			0.3		0.001
Distributed	AGS Ring Top	Injection	1.5 – 2.2	0.002	-
Thin				0.1	0.1
Thick				0.08	0.005
Distributed	AGS Ring Top	Transition	7	0.003	-
Thin				0.5	0.4
Thick				0.3	0.02
Distributed	AGS Ring Top	Extraction	27.5	0.001	-
Thin				0.2	0.02
Thick				0.6	0.005
Distributed	AGS Ring Top	Studies	10	0.0004	-

[20] 10^{14} p/s at 0.84 Hz. In appropriate areas, fault levels are detectable by radiation monitors instantaneously, and if interlocked, the beam will shut down within 9 seconds. It is estimated that three full energy beam spills may occur with this 9-second interval at the current repletion rate of 0.42 Hz. For areas where a fault may produce more than 20 mrem per fault, a system of access controls, such as barriers and locked fences are used and the area is upgraded to one of the radiation controlled areas described in the C-A OPM, Section 9.0 series.

Table 4.5.3.j Fault Levels at AGS Ring Penetrations[21]

Area of Interest	Fault Dose Equivalent per AGS Pulse (mrem/pulse)
C-14 Escape Hatch	30
Booster/AGS Interface	5
Linac/AGS Interface	30
Road over AGS Berm	50
North Conjunction Area	50
Pipes (Weakest Case)	100
Fan House Ducts (Weakest Case)	500
Entrance Labyrinths (Weakest Case)	10
Plug Doors (Weakest Case)	10
AGS-Booster Trench	500
Side Wall Interface w/Target Bldg 912 (Weakest Case)	10,000

Near J-10, beginning at the onset of catching and scraping for studies, transition and extraction losses, and extending at least 15 m past the most forward point of these losses, an overlying earth shield 6.3 m thick plus 0.6 m concrete with a berm rise over run of 1 to 2 is constructed. This reduces annual dose equivalent in Buildings 919 and 921 to less than 25 mrem in one year for an individual.

If J-10 is not used, studies, transition and extraction losses occur near E-20. Beginning at the onset of these losses and extending at least 15 m past the most forward point at which these

[21] The attenuation factors are taken from the Beavis Report (D. Beavis, Ring-Me, Potential Radiation Fault Levels from Beam Faults in the AGS Ring, AGS/EP&S/ Technical Note No. 138, October 1991). The source term used by Beavis was multiplied by 3.3 for the purposes of this tabulation in order to account for the potential 10µA proton beam operations at 100% duty factor (3000 AGS pulses/h). Protection is shielding, interlocking radiation monitors, fences and access controls.

losses occur, an overlying earth shield 6.9 m thick plus 0.6 m concrete is constructed. The side of the berm has a rise over run of 1 to 2. This reduces dose equivalent in Building 911 to less than 25 mrem in one year.

At the onset of injection losses and extending at least 15 m beyond the most forward point at which these losses occur, an overlying earth shield at least 5.1 m thick plus 0.6 m concrete is constructed. The berm rise over run is 1 to 2. This reduces dose equivalent to below 25 mrem in one year for persons in Buildings 931A and 931B.

In the analysis for direct radiation, the AGS Ring shield is visualized as 25 slabs of side shield of varying thickness in order to estimate the number of emerging neutrons which contribute to dose equivalent at a distant point. The closest point in the analysis is 15 m from the base of the AGS berm, which is the approximate location of the fence. Additionally, a direct radiation component from neutrons emerging from the top of the berm is included. The furthest point used in the calculation of direct radiation exposure is 150 m since additional shielding from interposed buildings, trees and hills is not accounted for.

The shield is at least 6 m of earth-cement mixture, or soilcrete as it is sometimes called, between the major loss points and occupied areas, and at least 4.8 m of earth between the remaining loss points and unoccupied areas. Annual dose equivalent from direct radiation to workers in Building 911 is estimated to be less than 5 mrem per year. The annual dose equivalent to the nearest person from skyshine is estimated to be much less than 1 mrem. For uncontrolled areas where buildings may exist, the maximum fault dose rate within the nearest occupied building is less than 5 mrem in one hour. Actual doses as measured by TLD studies show that these computed values are very conservative.

An AGS Ring Shield Upgrade Group was formed in 1988 to define the maximum beam losses for future running and to prepare a proposal for additional radiation protection. Their work is described in a number of papers.[22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38]

The locations of interest are: 1) Buildings 911, 919, 921, 928 and 929 where they are penetrated by direct radiation from losses in sections A and J of the AGS Ring, and by distributed losses, 2) occupied and unoccupied surfaces directly above a fault condition, and 3) areas affected by skyshine.

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[22] Th. Sluyters to D. I. Lowenstein, " AGS Ring Shield Upgrade Group, BNL Memorandum, July 26, 1988.
[23] G. Bennett, "Skinny Shield Studies/Calculations," Informal Note (July 19, 1988).
[24] E. T. Lessard to AGS Ring Shield Upgrade Group, "Design Criteria," BNL Memorandum, August 9, 1988.
[25] J. W. Glenn to AGS Ring Shielding Upgrade Group, "Short Meeting on Wed. August 31," Informal Memorandum, August 31, 1988.
[26] E. T. Lessard to J. W. Glenn, "Skyshine Transfer Function, On and Off Site," BNL Memorandum, September 21, 1988.
[27] AGS Staff, Shielding of the AGS from the Conversion Program, Accelerator Department, Brookhaven National Laboratory, Upton New York, 11973, A Report Prepared for the AEC Advisory Panel on Accelerator Safety (June 15, 1966).
[28] G. Bennett, L. Blumberg, C. Distenfeld, H. Foelsche, W. Moore, T. Toohig and G. Wheeler, Shielding of the North Experimental Facility and the Slow External Beam Extension, Accelerator Department, Brook haven National Laboratory, Upton New York, 11973, A Report Prepared for the AEC Advisory Panel on Accelerator Safety (February 25, 1970).
[29] H. Foelsche, "Expected Running and Maintenance Schedule for AGS Shield Upgrade," Informal Memorandum, September 27, 1988.
[30] A. Stevens, "Comparison of CASIM Calculation with Bennett's Flip Target Experiment," Informal Memorandum, October 4, 1988.
[31] K. A. Brown to J. W. Glenn, "Beam Losses and Residual Activation in the AGS," BNL Memorandum, October 4, 1988.
[32] A. J. Stevens to J. W. Glenn, "Preliminary Estimate of Skyshine from AGS Ring," Informal Memorandum, October 10, 1988.
[33] E. T. Lessard to J. W. Glenn, "AGS Ring Shielding Upgrade Group and Goals," BNL Memorandum, November 4, 1988.
[34] K. Brown, J. W. Glenn, S. Musolino, A. Stevens, R. Thern, "AGS Shield Tests," AGS Studies Report, Number 245 (November 21, 1988).
[35] E. T. Lessard to J. W. Glenn, "AGS Shielding Upgrade Analysis," BNL Memorandum, December 8, 1988.
[36] K. Brown to J. W. Glenn, "Losses and Activation in the AGS," BNL Memorandum, December 8, 1988.
[37] E. T. Lessard to J. W. Glenn, "AGS Shielding Upgrade Analysis: Revised Loss Assumptions and Close to Shield Estimates," BNL Memorandum, January 5, 1989.
[38] H. Foelsche and E. T. Lessard to J. W. Glenn, "Specific Shield Requirements for the AGS Ring Upgrade," January 23, 1989.

The following assumptions are made: 1) full beam loss, 10 microamps operation at 100% duty factor, produces the maximum dose rate, and 2) hot spot or point losses as viewed from the outer shield surface are distributed over 16 m.

Dose to people is from neutron and gamma radiation which result from high energy particles penetrating and interacting in the outer overlying layers of the shield. The integrated number of particles emanating from each 1 m section of shield surface area was computed. The center of each small section is termed a node. Radiations are assumed to emanate semi-isotropically from each node to all points on the surface. Dose at any point on the Laboratory site was based on radiation emanating from all nodes, and based on assuming the entire shield surface dose was from neutrons. Most of this dose is from the thinnest part of the side shield which is near the top of the berm. Dose directly through the side shield, which is very thick at ground level, is a small fraction of dose from radiations which shine down from the top of the berm. In addition to dose from this radiation, the dose from high energy particles which penetrate and interact in the air column above the surface of major loss points, the skyshine dose is calculated from standard methods.[39]

For persons occupying buildings, local shielding from the structure was assumed to reduce skyshine dose. Assuming that the dosimetrically significant energy of the neutron flux resulting from skyshine at Building 911 is between 0.5 and 3 MeV[40, 41] 15 cm of concrete presented by the walls and roof reduces neutron dose by a factor of 2 to 10 (see Figures 61

[39] G. R. Stevenson and R. H. Thomas, "A Simple Procedure for the Estimation of Neutron Skyshine from Proton Accelerators," Health Phys. 46, 115-122 (1984).
[40] J. M. Zazula, D. Filges and P. Cloth, "Sky- and Groundshine Phenomena and Related Radiological Quantities Evaluated fro the Environment of a High Current Spallation Facility," Particle Accelerators 21, 29-42 (1987).
[41] C. Distenfeld and R. Colvett, "Skyshine Considerations for Accelerator Shielding Design," Health Physics Division, Brookhaven National Laboratory, Upton New York 11973 Undated.

through 64 of NCRP Report No. 38[42], footnote 46). A dose reduction factor of 2 was used to account for local shielding. Occupancy of buildings is assumed to occur for 2000 of the 3800 hours of AGS operation during a year. Annual dose equivalent to persons in buildings has been shown to be acceptably low.[43] One factor was conservatively not used to reduce the dose, a factor to account for a 20% increase in density of soilcrete relative to ordinary earth. This provides an extra margin of safety into the calculations.

During AGS studies, the beam dump can receive the full AGS beam. Studies are planned to use 4.9% or less of the maximum available beam and to occur at 10 GeV or less. Typically studies are conducted over several 8 hour shifts periodically throughout the running period.

Fixed Targets

In target caves and leading up to the target station, continuous scraping of beam routinely occurs, about 2%. Target caves have 3.6 m heavy concrete shielding on the top and sides. Openings to target caves are concrete, steel and earth labyrinths. Typically, only 50% of the beam interacts in the target with the remainder entering a beam stop or being transported to a sequential target. A typical beam stop has a length of 16 meters and a radius at the front end of 3 to 4 m narrowing down to 1.5 meters at the back end. Typically, beam stops are made of iron with an outer shell of 1.2 m of heavy concrete.

The shielding for the primary beam switchyard and transport lines is typically 2.4 to 3 m of heavy concrete on the top and 3 to 3.6 m on the sidewalls. Some typical target stations have received up to as much as 5 x 10^{13} protons per pulse repeated every 2.5 seconds, i.e. 2 x 10^{13} p/s.

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[42] Protection Against Neutron Radiation, NCRP Report No. 38, National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Bethesda, MD 20814 (1987).
[43] Section 6.1.7.3 of AGS SAR, dated August 11, 1993.

Typically, the inside of a target station is 2.7 m in height and 3 m in width and it varies in length. The beam height is 2 m above the floor. Up to full beam flux, 2×10^{13} p/s, is expected to interact in some target stations; thus, these stations are shielded with up to 3.6 m of heavy concrete on the top and 4.8 m of heavy concrete on the sides. With the exception of slightly greater losses near target caves, it is assumed that a continuous loss of 1% uniformly distributed along the beam line occurs during operations. Typically primary beam lines are 150 meters in length, which translates to a planned loss per unit time per unit length of 1.3×10^{9} p/m-s. An occasional brief, controlled point loss occurs, such as that from putting a flag in the beam, and is about 2%.

The shielding for the U and V line includes earth rather than heavy concrete blocks as on other parts of the experimental areas. Openings are concrete labyrinths. Normal beam losses in the transport line result from scraping 1 to 2% of the beam. In order to run the U/V transport line at full flux, 2×10^{13} p/s, the earth shield over the transport line was increased from 3 m to 4.8 m. The U target station is a mix of light and heavy concrete, earth and steel plate. At present the U-line is only used for low intensity exposures.

Losses and the resulting routine and fault dose rates for typical, historical[44] high energy physics experiments in Building 912 and the U and V lines are summarized in the Table 4.5.3.k. Future high intensity proton beam experiments such as MECO and KOPIO are anticipated to be run at AGS in the first decade of 2000. The same calculational methods used for other AGS experiment doses will be utilized for MECO and KOPIO shielding design. If necessary, the SAD will be updated by appending the safety analyses of these experiments and any relevant ASE requirements will be developed and approved before operation of these experiments.

[44] AGS SAR, Sections 6.1.8 and 6.1.8.1 through 6.1.8.9, August 11, 1993.

Table 4.5.3.k Flux Loss and Radiation Level Summary for Historical Primary Beam Lines on Experimental Floor of Building 912 (Extracted Beam at 27.5 GeV)

Shield Type	Shield Surface of Interest	Routine Dose Rate[45] (1 x 10^{14} p/s)[46,47] mrem/h	Fault Dose Equivalent per AGS Pulse[48,49] (1 x 10^{14} p/s at 0.84 Hz) mrem/pulse
Switchyard	Top	5 - 1000	-
	Side	-	0.1 – 10
	Gate	-	1
	Side, Trench 1	-	30
	Top, Column A7	-	70
Transport Lines for A, B, C, D, U and V Line	Top	5 - 1000	-
	Side	0.5 - 50	-
	Gates	-	0.1 – 3
	Sides, Trenches	-	0.04 – 40
	Top, Column Penetrations	-	0.04 – 40
Typical Target Cave (6 m from target station)	Top	5	-
	Side	0.5	-
Typical Target Station	Top	350	-
	Side	35	-
Typical Target Stop	Top	100 – 200	-
	Side	-	20 - 40
Secondary Beam Lines		5 - 10	-
Labyrinth Openings/Gates		100 - 500	-
Trenches		50 - 200	-

[45] D. Beavis, C Target Cave Design and D Line Radiation Measurements, July 17, 1991.
[46] The dose rates are extrapolated form routine archival radiation surveys and fault studies taken during proton operations.
[47] A layer of controls are in place to limit target stations to receive below the assumed flux of 1 x 10^{14} p/s. This value was chosen to bound the potential routine dose rates.
[48] In appropriate areas, fault levels are detectable by radiation monitors instantaneously, and if interlocked, the beam will shut down within 9 seconds. It is estimated that three full energy beam spills may occur with this 9-second interval at the current repletion rate of 0.42 Hz. For areas where a fault may produce more than 20 mrem per fault, a system of access controls, such as barriers and locked fences are used and the area is upgraded to one of the radiation controlled areas described in the C-A OPM, Section 9.0 series.
[49] These maximum fault levels are extrapolated from fault studies with proton beam and the weakest shield locations were assumed (Reference – D. Beavis, H. Brown, I-H Chang, A. Etkin, J. W. Glenn, S. Musolino, A. Pendzick, P. Pile, K. Reece, A. Stevens, and K. Woodle, SEB Fault Studies Summary, May 3, 1990). Protection is shielding, interlocking radiation monitors, fences and access controls.

AtR

Calculations[50] of the prompt radiation dose in regions exterior to the berm over the AtR have been performed. The calculation assumes beam intensity equivalent to 2 x 10^{11} protons per bunch, and that 114 bunches are delivered to each collider ring. This is equal to the ASE intensity limit of 2.4 x 10^{13} protons per ring. The original design calculations also assumed twice the current regulatory value of the neutron quality factor. Thus, the more realistic estimates for dose, half those presented in the design calculations, are presented in this section.

Most regions of the AtR line experience very small beam loss, about 0.05% of the injected beam at a single point such as a magnet and 0.1% over the entire length of the line. A beam stop is located in the AtR line where the X and Y lines split from the W line. This dump is assumed to absorb 100 times the beam lost in the rest of the line. A summary of the calculation results is given below. The Big Bend Region is the X and Y injection arcs where the magnet elements are “dense”. The Other Regions are upstream of the injection arcs where the magnet elements are “sparse”. In the “dense” magnet regions, the generations of cascade interactions occur spatially closer to each other, thus causing higher peak fluence closer to the original interaction as compared to the “sparse” magnet regions. The dose equivalent rates were computed to be 0.13 mrem/h from the Big Bend Region and 0.08 mrem/h at Other Regions. Annual dose equivalents from each region with gold and polarized proton running are summarized in Table 4.5.3.l.

[50] A. J. Stevens, AD/RHIC/RD-83, Analysis of Radiation Levels Associated with Operation of the RHIC Transfer Line, December 1994.

Table 4.5.3.l Annual Dose Equivalent

	Big Bend Region	**Other Regions**
Au	138 mrem	81 mrem
Protons	16 mrem	9 mrem
Total	**154 mrem**	**90 mrem**

The maximum loss over 10 seconds is of interest for determining the sensitivity of Chipmunk response. The least sensitive area would be “other regions”. For this case, Au is 0.72 mrem/hr and protons are 1.56 mrem/hr.

The computed dose rates on the berm over the AtR are summarized in Table 4.5.3.m below. These dose estimates were very conservatively computed and fault studies show actual doses to be much lower. Two distinct, credible cases were examined: (1) the loss of full beam on an arbitrary point fives time per year which persists for two AGS pulses, and (2) an order of magnitude higher loss than normal, 0.5% at a point and 1% over the length of the AtR line for 5% of the collider fills in a year. During operation of RHIC, Thomson Road is posted as a Controlled Area to assure that dose limits are not exceeded for untrained individuals.

Table 4.5.3.m Fault Dose Equivalent Rates

	Big Bend Region	**Other Regions**
Two AGS pulses or 4.8 x 10^{12} 28 GeV protons lost at an arbitrary point 5 times/yr	(6.3 mrem/fault) 31 mrem/yr	(3.5 mrem/fault) 17.5 mrem/yr
0.5% point loss for and 1% total loss for 5% of the fills each year	77 mrem/yr	45 mrem/yr.
Total	**108 mrem/yr**	**62.5 mrem/yr**

RHIC

Systematic beam losses at the superconducting collider are limited by the ability of the magnets to sustain their superconducting state in the presence of particle losses. Particles leaving the beam pipe deposit energy in the form of a cascade of hadronic and electromagnetic particles. These interactions result in a significant temperature rise within a few meters from the loss point. A temperature rise of more than 0.5 K is sufficient to destroy the superconducting state of the Nb-Ti wire, which is known as a quench. Several hours may be required to cool the magnets back down to the required superconducting temperature and during this time, the experimental program is stopped. The approximate energy deposition needed to initiate a magnet quench is 4 mJ/g of superconductor and can be achieved by as little as one part in 104 of the circulating beam. Because such a small amount of beam loss can cause significant disruption to the experimental program, the collider is effectively a loss free facility. Small amounts of particle losses are cleaned by collimators, beam scrappers and a rapid acting (<1 ms) beam removal system that protects the magnets from the onset of beam loss by directing the beam into the beam dumps at the 10 o'clock areas of the ring.

The Collider beam dumps on either side of the 10 o'clock intersection region accounts for about 85% of the total beam energy loss. This loss has been conservatively analyzed to show that the berm shielding is sufficient to limit the dose rate to the nearest offsite location to < 0.5 mrem/yr.[51] A small area of the shield berm over each of the beam dumps is fenced and locked to control access for ALARA purposes.

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[51] Presentation to the Radiation Safety Committee on April 3, 1996 by A. J. Srevens in RSC files.

Collimators, primary and secondary, located on either side of the 8 o'clock intersection region have been examined to determine the potential dose rates from their usage.[52] Assuming that 20% of the beam in each ring interacts on the collimator and, at most, 10% of the stored beam in an hour results in dose rates well below 0.5 mrem/yr at unposted onsite and at the nearest offsite locations.

All the multi-leg penetrations in the Collider were analyzed with the method of Gollon and recalculated by Stevens[53]. The calculated results were then amended by Gollon to conform to the as-built conditions[54].

For emergency ventilation ducts, the computed doses at the berm surfaces range from 25 to 416 mrem. At the vent fan covers, at least 3 feet above the berm, the doses range from 14 to 238 mrem. Those areas that have excessive dose are within fenced and posted areas that are locked to prevent entry during Collider operations.

Dose calculations for access and emergency egress labyrinths and escape hatches show that doses range from 1 to 35 mrem.

There are a number of straight through penetrations into Collider beam enclosures. They are cylindrical shafts used for survey and large rectangular shafts on either side of the 6, 8, 10 and 12 o'clock experimental halls to permit cryogenic piping to bypass the experiments. These calculations[55] result in doses at penetration exits that range from 6 rem for a large rectangular cryogenic piping shaft, to 110 mrem for 12-inch cylindrical shaft. It is noted that for a person standing besides the opening instead of directly over it, the dose would be a factor of 10 lower. To prevent the possibility of causing these doses, personnel are excluded from these shafts by a 6

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[52] A. J. Stevens, AD/RHIC/RD-113, Radiation Safety Considerations Near Collimators, April 1997.
[53] RHIC SAD, Appendix 16, Shielding of Multi-Leg Penetrations into the Collider Tunnel, October 1999.
[54] P. J. Gollon, AD/RHIC/RD-76A, Amendment to Shielding of Multi-Leg Penetrations into the RHIC Collider, July 1996.
[55] RHIC SAD, Appendix 19, Evaluations of Straight Through Penetrations, October 1999.

foot fence and locked gates. These fenced areas are swept by the operating shift before allowing beam operations.

Dose rates from muons have been calculated to be very small, well below 0.5 mrem/yr at all locations[56].

TLD studies have confirmed that posting the entire RHIC facility as a Controlled Area is adequate.

4.5.3.3. Induced Residual Activity

Induced residual activity is similar at all C-A accelerators and experiments, the differences caused by the beam intensity and duration. Thus the specific activities vary. The maximum activities are produced at the AGS and target stations. These activities, which bound all others, are discussed in this section. Information on the induced residual activity of facilities other than the AGS may be found in the original SADs for those facilities.

Losses of high-energy particles during AGS acceleration can initiate reactions in beam pipes, magnets, extraction septum, and the dump/scraper. These interactions produce secondary particles such as neutrons, protons and pions. At each interaction point, the nuclei of atoms struck by the high energy primary or secondary particles fragment and result in a range of lower mass nuclei, some of which are radioactive. It was, therefore, necessary to consider the planned losses in the AGS and determine the magnitude of the radiation hazard produced by the induced activity.

The materials used in construction of the C-AD experimental areas are limited in number, the most important being iron, steel, copper, aluminum, concrete, oil and plastic. These

[56] A. Stevens, AD/RHIC-46, Radiation from Muons from RHIC, 2/1/89.

metals and materials are generally not used in their pure form; that is, they have welds, or they are alloyed with other metals, or they are parts of beam-line components. Thus, irradiation produces a variety of radionuclides in any given item. On the basis of studies on the AGS radioactive waste stream, nuclides ranging in half-life from days to years are formed in these materials. Table 4.5.3.n summarizes these nuclides.

Table 4.5.3.n Summary of AGS Radionuclide Production

Irradiated Material (Predominate Material)	**Nuclide**
Plastic, Oil	^{7}Be, ^{22}Na, ^{46}Sc, ^{54}Mn, ^{57}Co, ^{60}Co, ^{68}Ga, ^{88}Zr, ^{113}Sn, ^{124}Sb, ^{125}Sb, ^{133}Ba, ^{134}Cs, ^{207}Bi
Concrete	^{7}Be, ^{22}Na, ^{46}Sc, ^{54}Mn, ^{57}Co,^{58}Co, ^{60}Co, ^{65}Zn, ^{110}Ag, ^{134}Cs
Aluminum	^{7}Be, ^{22}Na, ^{54}Mn, ^{57}Co,^{58}Co, ^{60}Co, ^{65}Zn, ^{68}Ga, ^{95}Nb, ^{110}Ag, ^{33}Ba, ^{134}Cs
Iron, Steel	^{7}Be, ^{22}Na, ^{46}Sc, ^{54}Mn, ^{59}Fe, ^{56}Co, ^{57}Co, ^{60}Co, ^{65}Zn, ^{68}Ga, ^{75}Se, ^{95}Nb, ^{110}Ag, ^{113}Sn, ^{124}Sb, ^{125}Sb, ^{133}Ba, ^{134}Cs, ^{207}Bi
Copper	^{7}Be, ^{22}Na, ^{54}Mn, ^{57}Co,^{58}Co, ^{60}Co, ^{65}Zn, ^{68}Ga, ^{110}Ag, ^{133}Ba, ^{134}Cs

Studies[57] of beam loss and activation at the AGS have provided a prescription to predict activation and resultant exposure rate at particular locations in the AGS Ring. Residual exposure rate varies around the Ring and is presently 5 mR/h to 5 R/h. The highest levels occur at the extraction region in the F superperiod. The exposure rate in the G, H, I and J parts of the

[57] K. Brown, "Beam Loss and Induced Activation in the AGS," Accelerator Division Technical Note 337 (April 9, 1990).

AGS Ring are an order of magnitude less than in the F superperiod, and in the remaining superperiods levels are three to four orders of magnitude less. Available data at the AGS indicate that the exposure rate falls off according to the following relationship for the upstream (us) portions of superperiods:

$$X_{us} = 4.1 \text{ x } 10^{-14} E^{1.2} P \ln(1 + T/\tau)$$

where:

X_{us} = exposure rate at 30 cm, mR/h

E = proton energy, GeV

P = proton loss rate, p/h

T = irradiation time, h

τ = cooldown time, h

Assuming AGS Ring operation of 3800 hours per year, and losses as indicated in Table 4.5.3.g, maximum calculated exposure rates were determined and the results summarized in Tables 4.5.3.o and 4.5.3.p. These design calculations have been shown to be conservative based on actual radiation surveys. All work during repairs and routine maintenance and modifications is planned by the Work Planning process. Part of this planning includes a detailed radiation survey of the area where work will take place. Estimates of individual and total job dose are made and reviewed by the appropriate radiation professional before the start of work. If the expected accumulated dose exceeds a given administrative limit, an ALARA Committee review is needed to see if further actions can lower worker doses before the work can begin. This process has worked well over the last 15 years to reduce the total worker doses to a fraction of the doses received in the past.

Table 4.5.3.o Proton Beam Loss in the AGS Ring and Resultant Activation Levels (R/hr) For 3800 Hours of Operation

Loss Type	**Number of Protons Lost per Year**	**Energy (GeV)**	**Exposure Rate at 30 cm After 1 Day Cooldown**	**Exposure Rate at 30 cm After 1 Month Cooldown**	**Exposure Rate at 30 cm After 1 Year Cooldown**
Injection	$6.6x10^{19}$	2.2	9.2	3.3	0.65
Transition	$7.4x10^{18}$	7	4.2	1.5	0.3
Ejection	$7.4x10^{18}$	27.5	22	7.8	1.5
Studies	$4.2x10^{19}$	10	36	13	2.6
Sums:					
Injection Region (L20)			5.8	2.1	0.4
Dump/Scraper Region (J10)			62	22	4.4

Table 4.5.3.p Historical Experimental Area Target Activation (R/hr) For a 20 Week Irradiation Period

Target	**Target Number of 28 GeV Protons Interacting per Hour**	**Exposure Rate at 30 cm After 1 Day Cooldown**	**Exposure Rate at 30 cm After 1 Month Cooldown**	**Exposure Rate at 30 cm After 6 Months Cooldown**
A	3.8×10^{15}	42	15	5
B	3.0×10^{15}	33	12	4
B'	7.6×10^{15}	84	30	10
C	7.6×10^{15}	84	30	10
C'	3.8×10^{15}	42	15	5
D	7.6×10^{15}	84	30	10

Currently, proton fluxes are 18 times less, 1.3×10^{13} ppp at a 2.4 second repetition rate, than those assumed in the calculations. Thus, the current levels 1 day post shutdown, which are on the order of 5 R/h at the accessible portions of the extraction area, are in agreement with the above projected values.

A beam dump/scraper about 2 m in length at J10 serves to catch 80 to 90% of the beam loss that occurs during acceleration and extraction. The remaining loss is spread over the 7 to 8 magnets downstream. The L20 septum magnet will catch most of the injection losses. In addition to absorbing the acceleration and extraction losses, the dump/scraper provides a place to safely deposit beams not injected into the experimental areas, such as during studies. The dump steel becomes radioactive due to high energy (>20 MeV) spallation reactions. The prescription used here indicates that dump radiation exposure levels may be up to 60 R/h at 30 cm one day after shutdown following a long running period at design intensities of 1 x 10^{14} p/s.

In order to reduce these levels, a shield is placed around the dump. The shield also reduces the soil activation outside the tunnel to levels below ALARA design considerations given in the BNL SBMS Subject Area on Accelerator Safety. In order to eliminate the exposure rate hazard from residual radiation levels in the dump and shield, a temporary shield can be put in place to virtually eliminate this source of radiation exposure to nearby workers.

External beam lines and target stations are made of materials which are similar to the materials in the AGS Ring with the exception of small amounts of target materials. Using the prescription for the AGS Ring, the predicted exposure rates for a 20-week running period are shown in Table 4.5.3.p., assuming half the protons interact in the target. Targets and target caves are periodically refurbished to upgrade or change experiments. Extrapolating irradiation periods beyond 20 weeks is not assumed.

The beam fraction which does not interact with the target is either transported to the next target in line or is captured in a beam stop. Beam stops are designed with re-entrant cavities to reduce the photon exposure rate to nearby personnel who may be working in the target cave. Since the early 1970s, it was clear the major portion of the AGS radiation burden is associated with equipment failures and maintenance. Substantial effort and expense was committed to improving the operational reliability and serviceability of components, which continues to be effective in reducing the radiation burden. In 1973, when 2.3 x 10^{19} protons were accelerated, the AGS Department incurred 80 man-rem from neutrons, which reflects leakage radiation, and a 655 man-rem total. In 1989, 4.5 x 10^{19} protons were accelerated and the staff incurred 3.8 man-rem from neutrons and a 58.7 man-rem total. In 1992, we incurred a total of 24.57 man-rem. It is concluded that shielding is satisfactory and that dose is largely associated with photon exposure during repairs on failed equipment.

The C-AD as low as reasonably achievable strategy since 1973 has been as follows:

a. schedule maintenance for longest cooldown time,

b. improve reliability of vacuum system,

c. improve reliability of beamline components,

d. keep history of equipment malfunction,

e. improve injection, acceleration, and extraction methods,

f. modify shielding near trenches, columns and penetrations,

g. install quick disconnects on vacuum system and magnet, water, and power cables,

h. develop radiation hardened equipment,

i. use close coupled shielding to reduce secondaries near targets,

j. establish guidelines for area access based on radiation level,

k. train on mock-up equipment,

l. design shielding for quick removal,

m. use remote areas for storage of hot equipment,

n. compile and assess personnel exposure data,

o. institute radiation work permit system,

p. use complete magnet assemblies for quick replacement,

q. simplify target alignment and storage,

r. use self-aligning magnet stands to simplify surveying,

s. reduce density of beam components to reduce serviceability problems,

t. use remote test points to trouble shoot magnets,

u. increase the number of radiation monitoring points, and

v. provide computer integration of radiation monitoring system.

When heavy ion running occurs, activation is at least an order of magnitude lower than during high-intensity protons are run.

4.5.3.4. Activated Cooling Water

If activation of water is possible, C-A cooling water systems consist of a primary system, which is a closed system. This closed system has direct contact with the equipment or material being cooled, such as a magnet, beam dump or a target material, and can be directly irradiated by primary or secondary beam. Radioactivity is thus produced directly in the closed cooling water systems. Experience indicates that ^{7}Be and ^{3}H are the two long-lived radionuclides that are produced. The estimates indicate mCi amounts of ^{7}Be and ^{3}H are produced annually. Some secondary cooling water systems or cooling tower water may also be slightly activated depending upon the system configuration. For ^{3}H and ^{7}Be, the estimated concentrations at the end of a typical annual running period are given in Tables 4.5.3.q and 4.5.3.r for cooling tower and closed loop cooling water systems.

In addition to direct activation of water, slight amounts of radioactivity which have been induced in the magnet materials and wind up as corrosion products, are picked up in the cooling water. The current AGS systems have µCi amounts of radionuclides such as ^{54}Mn, ^{22}Na and ^{65}Zn. Activated cooling water is in closed re-circulated systems that are de-ionized, which greatly reduces the amount of dissolved and suspended corrosion products.

Tritium is always produced in conjunction with gamma emitters so a gamma detector is sufficient to monitor the effluent. In the event of an inadvertent release, gamma radiation monitors in the sanitary waste system which receives AGS effluent are designed to trigger the diversion of radioactive water away from the BNL Sewage Treatment Plant and toward a lined hold-up pond for additional sampling and treatment.

Table 4.5.3.q Typical Radioactivity Concentrations in C-AD Cooling Tower Water Systems

Cooling Tower Name	Location	Tritium Concentration (pCi/L)	Comments
Exp. System Tower No. 1	911, 912	5×10^2	No other radionuclides
Exp. System Tower No. 2	912	<MDL*	Pb-212
Exp. System Tower No. 3	912	2×10^3	No other radionuclides
Exp. System Tower No. 4	912a	2×10^3	No other radionuclides
F-10 Cooling Tower	932	<MDL	No other radionuclides
B-902 System Tower	902	1×10^3	No other radionuclides
RFMG Tower System	928	5×10^2	No other radionuclides
LINAC Tower	930	2×10^3	No other radionuclides
Booster Tower No. 5	919	2×10^3	No other radionucides
PTR Cooling Tower	919	<MDL	No other radionucides
g-2 Tower System	919	<MDL	No other radionucides
RHIC Inj. Tower No. 6	1000P	<MDL	No other radionucides
Brahms Cooling Tower	1002	<MDL	No other radionucides
RHIC RF Cooling Tower	1004	<MDL	No other radionucides
RHIC Cryo Cooling Tower No. 7	1005	<MDL	No other radionucides
STAR Cooling Tower	1006	<MDL	No other radionucides
PHENIX Cooling Tower	1008	<MDL	No other radionucides
PHOBOS Cooling Tower	1010	<MDL	No other radionucides
NSRL Cooling Tower	957	<MDL	No other radionucides
He Reliquifier Cooling Tower	1005E	<MDL	No other radionuclides

*MDL = Minimum Detectable Level, ~ 300 pCi/L for tritium

Table 4.5.3.r Typical Radioactivity Concentrations in C-AD Closed Cooling Water Systems

Water Systems Name	**Location**	**Tritium Concentration (pCi/L)**	**List of Other Isotopes**
Main Magnet Water	911	4.5×10^5	Be-7, Mn-54, Co-56, Co-57, Co-58, Co-60
Special Injection	911	4.5×10^5	Be-7, Mn-54, Co-57, Co-58, Co-60
Fast Quad	TE Bldg.	1.1×10^5	No other radionuclides
C-Line Cooling	912	1.2×10^7	Be-7, Na-22, Sc-46, Mn-54, Co-56,Co-57, Co-58, Co-60, Zn-65
RF Cavity	928, 913	2.5×10^5	No other radionuclides
SEM	928, 913, 914, 912A	5.6×10^5	Be-7, Mn-54, Co-58, Co-60
LINAC Transport	930	4.5×10^4	No other radionuclides
Beam Stop (BLIP)	946	1.2×10^6	Be-7, Mn-54
Booster Magnet	914	3.2×10^5	No other radionuclides
Booster RF Cavity	914	1.5×10^5	Be-7
Chilled Water	911,913, 914	5.5×10^5	Na-22, Mn-54
F-10 Cooling	932	1.5×10^5	No other radionuclides
PA Cooling	951	3.8×10^5	Be-7
g-2 Cooling	919	2.5×10^5	No other radionuclides
Power Room	911	7.5×10^2	No other radionuclides
Multipole Cooling	911	1.2×10^3	No other radionuclides
H-10 Cooling	H-10	< MDL*	No other radionuclides
B-944 Test	944	1×10^4	No other radionuclides
Rectifier System	928	1.5×10^3	No other radionuclides
RF Power	928	< MDL	No other radionuclides
Choke	928	5×10^3	No other radionuclides
Chilled Water	928	< MDL	No other radionuclides
Linac RF	930	2.0×10^4	No other radionuclides
10th Station	930	2.5×10^3	No other radionuclides
Linac OPUS	930	2×10^3	No other radionuclides

Table 4.5.3.r Continued - Typical Radioactivity Concentrations in C-AD Closed Cooling Water Systems

Water Systems Name	Location	Tritium Concentration (pCi/L)	List of Other Isotopes
Linac Cavity #1	930	2×10^3	No other radionuclides
Linac Cavity #2	930	1.5×10^4	Na-22, Na 24
Linac Cavity #3	930	2.2×10^4	Na-22, Na-24
Linac Cavity #4	930	2×10^5	Na-22, Na-24
Linac Cavity #5	930	2×10^5	Na-22, Na-24
Linac Chilled Water	930	2×10^3	No other radionuclides
B919B Test	919B	1.5×10^4	No other radionuclides
B-925 Test	925	1.5×10^4	No other radionuclides
RHIC Injection	1000P	1.0×10^4	No other radionuclides
Brahms Cooling	1002	<MDL	No other radionuclides
RHIC RF PA	1004	<MDL	No other radionuclides
RHIC Cavity	1004	<MDL	No other radionuclides
STAR Magnet	1006	<MDL	No other radionuclides
STAR MCW	1006	<MDL	No other radionuclides
STAR PS	1006	<MDL	No other radionuclides
TPC Cooling	1006	<MDL	No other radionuclides
PHENIX Magnet	1008	<MDL	No other radionuclides
PHENIX PS	1008	<MDL	No other radionuclides
PHOBOS	1010	<MDL	No other radionuclides
PTR Cooling	919	<MDL	No other radionuclides
V-Target Water	919	1×10^8	Be-7, Na-22, Co-56, Co-57, Co-59, Co-60, Zn-65
NSRL Main Magnet	957	<MDL	No other radionuclides
NSRL Power Supply	957	5.0×10^3	No other radionuclides
He Reliquifier	1005E	<MDL	No other radionuclides

*MDL = Minimum Detectable Level, ~ 300 pCi/L for tritium

The AGS practice is to monitor closed system or contact cooling water prior to discharge, and planned release of cooling water follows receipt of analytical data showing acceptable levels for all radionuclides. Additionally, the metals content is monitored in both contact and secondary cooling waters. The practice and follow-up actions for contact waters are as follows:

a. monitor for radioactivity and metals,
b. transport to C-AD Storage Tanker Trailers at Building 974 for treatment by evaporation or to the BNL Environmental and Waste Management Services Division if the radiation level is higher than allowable for direct discharge into the sanitary waste system,
c. process metals "in-line" if high,
d. discharge to the sewage treatment plant if all aspects of the State Pollution Discharge Elimination System Permit are met, and
e. contract a waste disposal facility when all else fails.

Cooling water will also contain small amounts of short-lived radio-gases, $^{15}0$ and ^{13}N. The external radiation hazard from circulating these gases with cooling water is momentary, lasting 5 to 10 minutes post shutdown of the beam.

Regarding hazards from activated animal waste for NSRL; assume an animal sample receives a near lethal dose of 500 rad (5 Gy) from 1 GeV/nucleon iron ions. This corresponds to $4x10^8$ iron-ions for a 20 cm^2 beam-size, or $2.3x10^{10}$ nucleons at 1 GeV. For soft tissues, water comprises about 80% of mass. Assume a sample is made of water, presents a 20 cm^2 area to the beam and is 20 cm long. Given a 30 millibarn (mb) cross-section for tritium production from high-energy nucleon-collisions with oxygen, the total tritium created in a sample from a 500 rad dose is 22 pCi. The activated excreta of animals is not expected to be measurable nor is it a significant radioactive hazard.

Radioactive water drained or collected from the various radioactive cooling water systems is transferred to one of three 7000-gallon tanker trailers, which are usually located at Building 974. They can be moved by truck throughout the site to facilitate transferring of water for later use, or as waste. The tankers are stainless steel and are parked inside a Suffolk County Article 12 registered secondary containment when not being used to transfer water.

Steam heat can be supplied to the tankers to heat the water to prevent freezing in the winter and to slowly evaporate the water throughout the year. The vapor contains low levels of tritium oxide from the activated cooling water systems from which it was drained.

A NESHAPs Assessment was conducted for this air release. The first evaluation was conducted in October 2000, by BNL ESD as part of the C-A Department's implementation of the ISO14001 EMS requirements. In that evaluation, only releases during the cold weather were considered.[58] A second NESHAPs evaluation was completed in June 2001 when the decision was made to maintain the tanker water heated all year in order to minimize the volume of wastewater for waste minimization. This evaluation assumed 25,000 gallons of water was evaporated each year.[59] The release was computed to cause an insignificant annual dose to the offsite maximally exposed individual of the public, MEI, of 0.0000864 mrem/yr. This release has no adverse public or environmental effects. It is noted that the MEI dose is directly proportional to the volume of water released, so even if the release was 50,000 gallons/yr, the MEI dose would only be 0.0001728 mrem/yr. Water tanker evaporation dose to workers has been evaluated to be insignificant.[60]

[58] Memorandum from G. Schroeder to P. Callegari, dated October 10, 2000
[59] Memorandum from B. Hooda to P. Lang, dated June 25, 2001
[60] R. Karol, Radiation Hazards From C-A Water Tanker Tritiated Water Evaporation, March 6, 2002

4.5.3.5. Soil Activation and Groundwater Contamination

The technique for estimating groundwater activation is described in the various original C-AD facility SARs and SADs. For each significant beam loss location which can activate soil shielding, the time-averaged transport of ^{3}H and ^{22}Na concentrations from the position of their creation to the water table by the leaching action of rainwater is estimated. This leachate concentration is required to be less than 5% of the drinking water standard as per the BNL Subject Area on Accelerator Safety.[61] The drinking water standard is 20,000 pCi/L for ^{3}H and 400 pCi/L for ^{22}Na. If this condition is not met, then impermeable caps are required to cover the soil. These caps act like umbrellas to prevent leaching of the radionuclides from the soil to the water table.

The quantity calculated to determine the soil radionuclide content is the CASIM "star density" or inelastic collision density. This is the interaction density of hadrons above about 47 MeV. Calculations have shown that approximately 0.075 ^{3}H and 0.02 ^{22}Na atoms are created per CASIM star, adjusted to a 20 MeV threshold.

Summaries of known beam loss locations and groundwater contamination issues at C-AD facilities have been written.[62,63,64] Based upon the groundwater flow direction, soil pore velocity, and dispersion, it would take greater than 20 years for any contaminated groundwater to reach the BNL southern boundary, and thus there are no possible adverse health effects to the public. Several onsite potable water supply wells could be contaminated within a time frame of years

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[61] Accelerator Safety Subject Area, Design Practice for Known Beam Loss Locations.
[62] Memorandum for D. Lowenstein and E. Lessard to P. Paul, Beam Stops and Other Sources of Soil Activation at the AGS Complex, August 7, 1998.
[63] Investigation of the Tritium Release at Location Upgradient of BNL Well 054-067, December 10, 1999.
[64] Brookhaven National Laboratory g-2 Tritium Plume – AOC 16T Engineering Evaluation/Cost Analysis, December 2003.

following groundwater contamination caused by C-AD operations. Again, there are no adverse health effects to onsite personnel. A large number of groundwater monitoring wells are positioned to monitor C-AD facilities that contain activated soil shielding. This active surveillance program allows for rapid detection of a problem and quick response to stop the source. Furthermore, BNL is controlling the pumping of the most vulnerable supply wells onsite to prevent drawing contaminants toward them. (e.g., supply well #10 located east of the AGS experimental areas).

Groundwater contamination is an environmental issue related to the BNL EMS program where we are committed to protect our natural resources and is not a health issue to workers, onsite personnel or the public.

4.5.3.6.Activated Air

The main source of air activation is the interaction of primary and secondary particles directly with air nuclei. Air contains approximately 78.1 % N_2, 21% O_2, 0.5 % ^{40}Ar, 0.3 % ^{15}N, and 0.04 ^{18}O. Low energy beams are contained in the vacuum pipe of the accelerator or beam line and air activation with these beam types is low. At higher energies, especially protons, and when air gaps exist where the beam passes through air directly, air activation becomes more important. In addition, the large multiplicity of secondary particles produced as part of the cascade, both electronic and hadronic, processes can produce air activation even when the beam is contained in the vacuum line.

In general, the positron emitters ^{11}C ($t_{½}$ of 20.3 m), ^{13}N ($t_{½}$ of 9.97 m) and ^{15}O ($t_{½}$ of 122.2 s), along with ^{41}Ar ($t_{½}$ of 1.83 h, produced by thermal neutron absorption in ^{40}Ar) are most frequently observed.

By design, the Linac, Tandem, TtB, Booster, AGS, Fixed Target caves, U and V Lines, AtR and RHIC do not have forced exhaust ventilation during operation in order to minimize the release of activated air. The air activation is minimized by passing ion beams through vacuum tubes and minimizing the beam path through air in target caves. Helium-filled bags may be used in the beam path not enclosed in vacuum to reduce interactions and multiple scattering.

Following beam operations, fixed waiting intervals are specified in the C-AD OPM to enter primary areas in order to assure that doses to workers and experimenters are ALARA. The waiting intervals depend upon the ion beam species and the beam intensity prior to entry into the primary area.

For the NSRL facility, the Target Room in Building 958 is continuously ventilated to reduce odors from the specimens. The air activation estimate in the Target Room was made using MCNPX. The beam path length in air is 28 feet including the length of the re-entrant beam dump cavity. The room-averaged hadron flux greater than 20 MeV from interactions is 2.1×10^{-6} per cm^2 per incident 2-GeV proton, and the thermal neutron flux is 3.4×10^{-6} per cm^2 per proton. However, the room averaged flux of the incident beam particles is 6.8×10^{-6} per cm^2 per proton, which dominates the activation of air.

Given these fluxes, concentrations of various radionuclides were estimated using appropriate cross sections. For ^{39}Cl and ^{38}Cl, produced by spallation reactions with the argon in Target Room air, cross sections were estimated from Rudstram[65]. These were included because

[65] Barbier, M., Induced Radioactivity, Section 2.3. North-Holland Publishing Company, 1969.

they are sometimes detected in air samples at BNL accelerators. With the maximum annual energy flux of 3 × 10^{16} GeV per year on the beam stop given in Table 4.5.3.e, Table 4.5.3.s summarizes the annual-activity concentrations averaged over the Target Room volume which were conservatively computed ignoring radioactive decay and Target Room ventilation.

Table 4.5.3.s Annual-Activity Concentration Averaged over Target Room Volume And Annual Production Rate of Air Activation Products

Radionuclide of Interest	Volume Averaged Annual-Activity Concentration, Ci/cc	Annual Production Rate, Ci/yr
^{41}Ar	2.2×10^{-11}	2.6×10^{-3}
^{39}Cl	1.2×10^{-16}	1.4×10^{-8}
^{38}Cl	4.3×10^{-16}	4.9×10^{-8}
^{35}S	1.4×10^{-15}	1.6×10^{-7}
^{32}P	9.1×10^{-15}	1.0×10^{-6}
^{28}Al	7.0×10^{-13}	8.1×10^{-5}
^{22}Na	5.6×10^{-17}	6.3×10^{-9}
^{15}O	6.7×10^{-9}	7.4×10^{-1}
^{14}O	2.8×10^{-10}	3.2×10^{-2}
^{13}N	1.6×10^{-9}	1.8×10^{-1}
^{11}C	7.0×10^{-10}	8.1×10^{-2}
^{7}Be	1.9×10^{-13}	2.1×10^{-5}
^{3}H	7.7×10^{-15}	8.8×10^{-7}

Given these radionuclide quantities, the dose to the maximally exposed individual, MEI, of the public has been estimated using the Clean Air Act Code CAP88-PC. The standard BNL site-specific model was utilized with 10-year average wind rose, temperature, and precipitation and CY 2000 population data. The CAP88-PC model is designed to model routine, continuous airborne radioactive emissions that occur over the course of a year. The radionuclides listed in Table 4.5.3.s were modeled as if they were released in this manner. Aluminum-28 and oxygen-14 are not included in the CAP88-PC radionuclide library and thus were not included in the model. However, the source terms and half-lives of these radionuclides are so small that their exclusion has no affect on the conclusions of the evaluation. Chlorine-39 and chlorine-38 were also not included because their effect has no affect on the conclusion.

The calculation showed that the dose to the BNL site maximally exposed individual of the public at the northeastern site boundary is 9.7×10^{-6} mrem/yr.[66] This dose is six orders of magnitude below the 10 mrem/yr limit specified in 40CFR61, Subpart H, and a factor of ten-thousand times less than the 0.1 mrem/yr limit that triggers the NESHAPs permitting process. Therefore, no application for a permit was required for the NSRL and continuous monitoring of the release point is not required.

Normally, the Target Room is ventilated continuously to reduce odors from the biological specimens. The ventilation system will maintain the radionuclide concentrations at insignificant values in the Target Room. If the ventilation is off and irradiations and entries are still made over an 8-hour interval, the dose to an individual who spends an hour in the Target Room would be a small fraction of a mrem.[67] Thus, there are no significant hazards from loss of Target Room ventilation.

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[66] http://www.rhichome.bnl.gov/AGS/Accel/SND/BAF/BAFSADAppendix4.pdf, Appendix 4, BAF SAD, G. Schreoder, NSRL Facility/Process Radionuclide Evaluation, January 4, 2001.

[67] R. Karol, Dose to Individual in BAF Target Room Following Ventilation Failure, March 19, 2001 (Revised 4/19/01).

4.5.3.7. Skyshine

Radiation that extends several hundred meters from an accelerator shield or the top of an accelerator building is termed skyshine. Escaping neutrons through thin parts of the shield or roof causes skyshine. Roof shields are inaccessible, via access controls, during operations. The upward neutrons scatter in the air above the complex, and mixed gamma-neutron radiation arrives back at ground level. Ongoing monitoring shows that skyshine is a minor contribution to the annual dose to the public and workers. Annual environmental radiation measurements for offsite areas show that it is not measurable above natural background radiation levels. The measured skyshine levels are summarized in the BNL Site Environmental Report produced by the BNL Environmental and Waste Management Services Division.

Linac

Skyshine from the Linac beam is not a significant contributor to external dose due to the relatively low energy beam and the shield thickness. See the discussion later in this section regarding Linac to Booster injection skyshine for more details.

Tandem and TtB

Skyshine for the Tandem and TtB line is insignificant due to the very low particle energies.

Booster

The dose equivalent from skyshine due to neutrons emitted from the surface of an overlying beam line shield is given by Stevenson.[68] Neutrons emerge from the top of the shield and contribute to dose equivalent on the ground several hundred to several thousand meters away through interactions in the air column above the shield. The analytical function which describes this is:

$$H(r) = 3 \times 10^{-13}\, e^{-kr}/r^2$$

where H is the dose equivalent in rem per neutron moving upward through the shield at distance r from the source, k is the volume macroscopic dose-reduction cross section for skyshine radiation for neutron interactions in air, and r is distance from the source in meters. As deduced from Stevenson in Figure 7 of his report and inverting the value for effective absorption length, k equals 1.25×10^{-3} m^{-1} for 1.5 GeV neutrons, nominal Booster extraction energy, and 2×10^{-3} m^{-1} for 200 MeV neutrons, the injection energy from Linac.

A summary of the number of neutrons emitted from several locations which contribute 5 mrem at the site boundary and 25 mrem at onsite buildings that are uncontrolled areas or non-C-A facilities is given in Table 4.5.3.t. The closest non-C-AD uncontrolled location with full-time occupancy is the old BGRR complex. The closest uncontrolled C-AD facility is Building 911. Buildings 919 and 931 (BLIP) are both posted controlled areas.

[68] G.R. Stevenson, R.H. Thomas, "A Simple Procedure for the Estimation of Neutron Skyshine from Proton Accelerators", Health Phys. 46, 115-122 (1984).

Table 4.5.3.t Number of Neutrons Emitted from the Top of the Booster which Produce 5 mrem at the Site Boundary and 25 mrem at other Uncontrolled Areas or Non-C-AD Facilities

Location (Design Goal)	**Occupancy Fraction and Distance (m)**	**Injection (200 MeV)**	**Extraction and Studies (1.5 GeV)**
Site Boundary (5 mrem)	1, 1100 m	1.8×10^{17}	8.0×10^{16}
Former BGRR Complex (25 mrem)	1/3, 520 m	3.8×10^{18}	2.6×10^{18}
Building 911 (25 mrem)	1/3, 370 m	1.4×10^{18}	1.1×10^{18}
Building 919 (25 mrem)	1/3, 150 m	1.5×10^{17}	1.4×10^{17}
Building 931 (25 mrem)	1/6, 80 m	7.5×10^{15}	7.1×10^{16}

On-site facilities are of slightly greater significance than the site boundary. This is dependent on assumptions regarding local shielding and energy of scattered neutrons. The neutrons which scatter off the air back to the ground toward these buildings have an energy distribution nearly equivalent to the fast flux from a PoBe source (>0.5 MeV) and 0.5 feet of concrete or equivalent local shielding attenuates the neutrons by a factor of 20. This attenuation from local shielding increases the number of leakage neutrons that correspond to a given dose equivalent at a given, distant location and is included in the onsite estimates for skyshine. Occupancy of the Building 931 facility (BLIP), which is at 80 m, is during the day shift only, about 4 hours per shift according to Medical Department staff who has operated the facility for many years. This corresponds to one sixth of a Booster operating day. Occupancy of the former BGRR complex, Building 911 and Building 919 is 8 hours per day, which is one third of an operating day for the Booster. Therefore, it is reasonable to assume that Building 931 is the most restrictive location and that 7×10^{16} neutrons is the limiting design for neutrons contributing to skyshine from the Booster each year. Full-time occupancy and zero local shielding are conservatively assumed for the site boundary location.

ICRP Publication 21[69] lists the dose equivalent per unit neutron fluence for l/E spectra versus maximum neutron energy. If the analytical function by Stevenson is used to estimate dose equivalent from skyshine, the maximum neutron energy should be estimated from the maximum proton energy of the accelerator. For 200 MeV and 1.5 GeV, the conversion factors deduced from ICRP 21 are 8.1×10^7 and 5.9×10^7 neutron/cm^2 per rem respectively. A mean value of 7×10^7 neutrons/cm^2 per rem is used here. This conversion factor and the annual areal-dose design goal, which incorporates the design limit of 7×10^{16} neutrons from Table 4.5.3.t, are given in Table 4.5.3.u.

Table 4.5.3.u Total Annual Areal Dose Goal (rem-cm^2)

Shield Material	n/cm^2-rem	rem/cm^2
Earth or Concrete	7×10^7	1×10^9

In order to ensure that the design goal is met, an estimate of the annual area1 dose is computed based on 1) a Booster operating schedule of 200 days per year, 2) the shielding configuration near the dump and the extraction septum, and 3) the planned loss assumptions. Polarized proton and heavy ion modes make up 100 days of the annual running period, and unpolarized proton running makes up 100 days. Additionally, Booster studies require 70 operating days and about one third of the scheduled operating hours during those days. Based on

[69] International Commission on Radiological Protection, Data for Protection Against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15, ICRP Publication 21 [Pergamon Press, October (1973)].

studies at the AGS Ring[70], skyshine neutrons from a point source, such as the losses at the extraction septum and the dump/scraper, emerge from a berm surface area of $2x10^2$ m^2. For perspective, the top of Building 914 downstream of the septum is about $2x10^2$ m^2, and the top of the Booster Ring is about $2x10^3$ m2. Using a loss area of $2x10^2$ m^2, and the routine peak dose rates given in Table 4.5.3.t, the computed areal-dose equivalent is $3.4x10^7$ rem-cm^2 near the extraction septum and $9.3x10^6$ rem-cm^2 near the dump/scraper. The sum is 4.3×10^7 rem-cm^2 which is well within the design goal of $1x10^9$ rem-cm^2. Location specific estimates of annual dose from skyshine are given in Table 4.5.3.v. These estimates are overly conservative and TLD studies show that actual values are significantly lower.

[70] K. Brown, J. Glenn, S. Musolino, A. Stevens, R. Thern, "AGS Shield Tests", AGS Studies Report Number 245 (November 4, 1988).

Table 4.5.3.v Flux Loss and Sky Shine Exposure Summary

Loss Flux Location	Nucleon Energy (MeV)	Annual Areal Dose (200 m^2)	Corresponding Number of Leakage Neutrons (rem-cm^2/y)	Site Boundary Dose (mrem/y)	Closest Occupied Building Dose (mrem/y)
Injection dump/scraper	200	2.8×10^3	2.0×10^{11}	6×10^{-6}	7×10^{-5}
Acceleration dump/scrapper	700	9.6×10^5	6.7×10^{13}	4×10^{-3}	2×10^{-2}
Extraction septum	1500	3.4×10^7	2.4×10^{15}	2×10^{-1}	9×10^{-1}
Heavy ions stripper	1066	2.4×10^7	1.7×10^{15}	1×10^{-1}	6×10^{-1}
Studies dump/scrapper	1500	8.4×10^6	5.9×10^{14}	4×10^{-2}	2×10^{-1}
Total (assuming protons for 200d/y)		**4.3×10^7**	**3.1×10^{15}**	**2×10^{-1}**	**1**

Building 931 is the closest occupied on-site facility at 80 m to the various sources identified in Table 4.5.3.v, and personnel are expected to receive a total of no more than 1 mrem per year from skyshine. The skyshine dose decreases with distance from the source and diminishes by a factor of at least 4 at 150 m to Building 919 and by a factor of at least 30 at 370 m to Building 911. Given the accuracy of the skyshine analytical function and TLD studies, it is reasonable to conclude that the annual skyshine dose at nearby locations, such as Buildings 919, 925, 911, 928, 929 and 902, will be much less than 1 mrem.

Due to the proximity and elevation of Building 931 (BLIP) particle interactions in the earth on top of Building 914 and on top of the Booster Ring near the dump/scraper at D6 are a source of more radiation at Building 931 than radiation from high energy particle interactions in the column of air above the Booster. According to Table 4.3.5.v, about $3x10^{15}$ neutrons are estimated to leave the surfaces of Booster during the year. Radiation that originates at the surface realistically diffuses outward, rather than all going straight up into the air. About 50 mrem at Building 931 is estimated for a hemispherical source at the Booster surface. Adjusting for occupancy, the annual dose at Building 931 is 10 mrem from groundshine. Assuming full-time occupancy at Building 931 results in 20 mrem per year. Thus groundshine plus skyshine contributions still results in exposures below the ALARA design considerations. This additional exposure to neutrons from groundshine diminishes rapidly at distances greater than Building 931 since other buildings, earth and obstructions absorb or scatter the groundshine neutrons.

NSRL

Both the skyshine dose-rate estimate and the groundwater activation estimate, described later in this Chapter, are sensitive to targeting conditions. The maximum flux values listed in Table 4.5.3.e assume that the beam can be incident on either a target or the beam stop 100% of the time.

The skyshine dose rate was determined by first estimating the number of neutrons greater than 20 MeV emerging from the earthen berm surface, then applying a skyshine formula developed from past measurements made at the AGS. The estimate of the number of neutrons was made from CASIM calculations performed at 2 GeV incident energy in a simplified approximation of the geometry, a geometry that overestimates the emerging neutrons. Specifically, the berm was assumed to have a circular transverse cross-section, and the neutrons were summed over a ±45° section centered on the beam line.

CASIM estimates were made with both the beam incident on the beam dump and on a 0.25 interaction length plastic target. The worst case was with the target present, where the number of neutrons greater than 20 MeV per 2 GeV proton is 2×10^{-5}. For 1.5×10^{16} 2-GeV protons per year, the skyshine formula becomes:

$$rem/year = \frac{0.125 \times e^{-D/600} \times (1 - e^{-D/47})}{D^2}$$

where D is the lateral distance from the source to the dose point of interest in meters.

The closest building that at times is uncontrolled is Building 919 at D = 70 m. At this distance, the computed dose rate is about 0.02 mrem/yr.

AGS and Fixed Targets

Simple analytical functions[71,72,73] are used in order to estimate on-site and off-site dose equivalent. The external exposure limits of 5 mrem/y offsite and 25 mrem/y at uncontrolled onsite buildings are the basis for and are related to secondary design goals such as the thickness

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[71] G.R. Stevenson, R.H. Thomas, "A Simple Procedure for the Estimation of Neutron Skyshine from Proton Accelerators", Health Phys. 46, 115-122 (1984).
[72] K. Tesch, "A Simple Estimation of the Lateral Shielding for Proton Accelerators in the Energy Range 50 to 1000 MeV", Radiation Protection Dosimetry 11, 165-172 (1985).
[73] K. Tesch, "Comments on the Transverse Shielding of Proton Accelerators", Health Phys. 44, 79-82 (1983).

of shield needed to meet those dose goals. The following is a description of the methods used to derive secondary design goals in five steps, and a summary.

1. Dose Equivalent From Neutrons Emitted In An Upward Direction

The dose equivalent from skyshine due to neutrons emitted from the surface of an overlying beam line shield is given by Stevenson. Neutrons emerge from the top of the shield and contribute to dose equivalent on the ground several hundred to several thousand meters away as a result of interactions in the air column above the shield. The analytical function which describes this is:

$$H(r) = 3 \times 10^{-13} e^{-kr}/r^2$$

where H is the dose equivalent at ground level from secondary skyshine radiations in rem per neutron-emitted upward at distance r from the source, k is the volume macroscopic dose reduction cross section for skyshine radiation produced from neutron interactions in air, and r is distance from the source in meters. As deduced from Stevenson, $k = 1.18 \times 10^{-3}$ m^{-1} for 28.5 GeV maximum energy neutrons. Based on Stevenson, the dose equivalent calculated for distances less than 400 meters is overestimated, and according to their graphs, probably by a factor of 2 for 28.5 GeV.

2. Number of Upward Neutrons Which Yield the Annual Dose Design Goal

A summary of the number of neutrons emitted from several locations which lead to 5 mrem and 25 mrem at areas of interest is given in Table 4.5.3.w. The closest non-C-AD uncontrolled location with full-time occupancy is the retired Brookhaven Graphite Research Reactor (BGRR) complex. The closest uncontrolled C-AD facility is Building 911. Occupancy at the BGRR complex and Building 911 is assumed to be 40 hours out of 168 hours per week or 25% of a running period.

Table 4.5.3.w Number of Neutrons Emitted from the Top of D, A, B or C Lines Which Produce 5 mrem at the Site Boundary and 25 mrem at Other Uncontrolled and Fully Occupied Locations

Location (Design Goal)	**Occupancy Factor**	**D-Line (distance)**	**A-Line (distance)**	**B-Line (distance)**	**C-Line (distance)**
Site Boundary (5 mrem)	1.0	1.7×10^{17} (1400 m)	1.7×10^{17} (1400 m)	1.7×10^{17} (1400 m)	1.7×10^{17} (1400 m)
BGRR Complex (25 mrem)	¼	8.6×10^{17} (300 m)	1.2×10^{18} (350 m)	1.7×10^{18} (400 m)	2.4×10^{18} (450 m)
Building 911 (25 mrem)	¼	1.8×10^{17} (150 m)	3.4×10^{17} (200 m)	5.6×10^{17} (250 m)	8.6×10^{17} (300 m)
Building 923 (25 mrem)	¼	3.6×10^{17} (250 m)	3.4×10^{17} (200 m)	1.8×10^{17} (150 m)	7.6×10^{16} (100 m)

On-site facilities are of greater significance than the site boundary; however, this depends on assumptions regarding local shielding, building classification with regard to radiation safety, and energy of skyshine radiations. Building 923 is a controlled area, which contains radioactive materials. The nearest uncontrolled building is Building 911 which is closest to the D line. Assuming that the skyshine flux at Building 911 is equivalent in energy to the fast flux of neutrons from a PoBe source (>0.5 MeV), 30 cm of concrete will attenuate the skyshine by a factor of about 20. This factor of 20, used for onsite building local shielding raises the number of upward neutrons causing 25 mrem at a distance to 1.8×10^{17}. This is approximately the same as the site boundary goal. Therefore, it is reasonable to assume that the site boundary goal, 1.7×10^{17} neutrons, is the limiting value for upward neutrons for the AGS Ring and Experimental Areas.

3. Total Areal-Dose Equivalent Goal (rem-cm^2)

ICRP Publication 21[74] lists the dose equivalent per unit neutron fluence for 1/E spectra versus maximum neutron energy. If the analytical function by Stevenson is to be used to estimate dose equivalent from skyshine, the maximum neutron energy should be estimated from the maximum proton energy of the accelerator. For 28.5 GeV, the conversion factor deduced from ICRP 21 is 2 x 10^7 neutron/cm^2 per rem. Stevenson indicates that a 1/E spectrum applies to dry concrete, but he also indicates that there are fewer low-energy neutrons from earth shields since earth contains water.[75] On the other hand, Stevenson tabulates measurements which indicate that 2 x 10^7 neutrons/cm^2 per rem is appropriate for a neutron spectrum from high-energy proton accelerators with thick earth shields. In that same report, he gives a value of 1.5 x 10^8 neutrons/cm^2 per rem for iron, and this value reflects the fact that iron is transparent to low-energy neutrons. These conversion factors and the design goal which incorporates the value of 1.7 x 10^{17} neutrons from Step 1 are given in Table 4.5.3.x.

Table 4.5.3.x Neutrons Per Unit Area Per Unit Dose Equivalent at the Surface of a Thick Shield for the Condition of 28.5 GeV Protons Incident on a Target Behind the Lateral Shield and Total Annual Areal Dose Equivalent Goal (rem-cm)

Shield Material	**n/cm^2-rem**	**rem-cm^2**
Concrete	2x10^7	8.5x10^9
Earth	2x10^7	8.5x10^9
Iron	1.5x10^8	1.1x10^9

[74] International Commission on Radiological Protection, Data for Protection Against Ionizing Radiation from External Sources: Supplement to ICRP Publication 15, ICRP Publication 21 [Pergamon Press, October (1973)].
[75] G.R. Stevenson, "Dose Equivalent Per Star in Hadron Cascade Calculations", Divisional Report, European Organization for Nuclear Research, TIS-RP/173 (May 26, 1986).

Therefore, on-site and offsite external dose rate design goals are met if no more than 8.5 x 10^9 rem-cm^2 are allowed at the outer shield surfaces during the annual proton running period and if concrete or earth are used at the outer parts of the shield wall.

4. Dose Rate at the Surface of the Outer Shield Wall Per Proton Per Second Stopped behind the Shield Wall

There are simple analytical relationships reported by Tesch[76] for relating the surface dose equivalent to proton loss behind shielding, and these can be used to interpret shielding limitations imposed by the design goal of 8.5 x 10^9 rem-cm^2. For these calculations, the distance from the target to the inner surface of the overlying shield was assumed to be 1 m. In performing shield calculations, integration is carried out over the overlying shield area which in many cases can be assumed to be over a ± 45º vertical angle. Lateral shield surface dose rates at the AGS are best approximated by a line source inside the ring instead of a point source when using the Tesch analytical functions. That is, the ring's beam loss is not really assumed to be a point, and rather it is a line about 16 m long. This is borne out by dose rate measurements at the surface of the AGS Ring following a planned loss, and by activation studies inside the tunnel. In order to account for the additional shielding offered by a magnet section, the mean chord length of magnets in the vertical angle of ± 45º is assumed to be 42 cm. In Table 4.5.3.y, the dose rate in mrem/h per proton lost per second offered by 3 different types of common AGS shielding arrangements is shown: 1) an overlying shield of 42 cm of magnet iron and heavy concrete in column 2, 2) 42 cm of magnet iron and soil in column 3, and 3) 42 cm of magnet iron, varying thick-nesses of iron plate plus 60 cm of heavy concrete at the outer surface in column 4.

[76] K. Tesch, "A Simple Estimation of the Lateral Shielding for Proton Accelerators in the Energy Range 50 to 1000 MeV", Radiation Protection Dosimetry 11, 165-172 (1985).

Table 4.5.3.y Dose Equivalent Rate at the Surface of a Lateral Shield from 28.5 GeV Protons for Different Overlying Materials

Total Thickness of Shield[a], cm (ft)	**Heavy (Ilmenite loaded) Concrete**	**Earth**	**Iron Plate (with 2 ft of heavy concrete outside)**
300 (10)	5.5×10^{-11}	1.4×10^{-9}	1.9×10^{-16}
360 (12)	8.4×10^{-12}	4.4×10^{-10}	2.6×10^{-18}
450 (15)	5.4×10^{-13}	7.4×10^{-11}	4.2×10^{-21}
600 (20)	5.3×10^{-16}	4.4×10^{-12}	1.0×10^{-25}

a: The shield thickness listed here does not include the 42 cm of magnet iron; however, the effect of magnet iron is included in the estimate of dose rate.

5. Average Surface Dose Rates Necessary to Meet Design Goals

Three assumptions are needed to estimate areal dose and average shield surface dose rate in order to meet design goals:

1) a running period of 20 weeks at 5×10^{13} protons per pulse at 28.5 GeV and 1 pulse every 2.5 seconds; that is, 2.4×10^{20} total protons at the average rate of 2.0×10^{13} p/s,

2) each beam line is designed to take 2.4×10^{20} protons per annual running period (this is the projected maximum design, most programs assigned to a beam line take only a portion of the full beam), and

3) upward neutrons from a point source of protons emerge from a shield surface area of 1.9×10^{6} cm^2 (2000 ft^2). The neutron leakage of the AGS Ring was measured in the J superperiod using the J19 flip target as a point source. The target was about 700 cm (23 ft) below

the shield top. The effective area of the neutron emission was estimated using plots of surface radiation level versus position both transversely and longitudinally outside the shield top.[77]

Based on these assumptions, the following dose rates at the surface of a heavy concrete shield and the annual areal doses are estimated and listed in Table 4.5.3.z.

Table 4.5.3.z Lateral Shield Thickness Versus Surface Dose Equivalent Rate and Areal Dose Equivalent for 2.4 x 10^{20} Protons in an AGS Beam Line (Sect. 4.1.1)

Thickness of Heavy Concrete cm, (ft)	**Surface Dose Rate mrem/h**	**Annual Areal Dose Rem-cm^2**
300 (10)	$1.1x10^3$	$7.0x10^9$
360 (12)	$1.7x10^2$	$1.0x10^9$
450 (15)	$1.1x10^1$	$7.0x10^7$
600 (20)	$4.4x10^{-4}$	$2.8x10^3$

While the table shows heavy concrete, other materials may be used. In general, 1 foot of heavy concrete (density 3.5 g/cm^3) may be substituted for 1.6 feet of earth (density 1.8 g/cm^3), for 1.25 feet of concrete (density 2.3 g/cm^3) or for 0.5 feet of iron. If iron is used as a lateral shield, the outer 2 feet must be concrete or earth since iron is transparent to low-energy neutrons.

The total annual areal dose goal, 8.5 x 10^9 rem-cm, may be met by ensuring that the planned locations for beam loss have at least 300 cm or 10 ft of heavy concrete above them or the equivalent thickness of other materials. This is true for the known loss points for the known small fraction of the beam in the AGS Ring which are shielded by a mixture of sand and soilcrete to a thickness of 690 cm or 23 ft, which is about 300 cm equivalent heavy concrete, and for the

[77] K. Brown, J. Glenn, S. Musolino, A. Stevens, R. Thern, "AGS Shield Tests", AGS Studies Report Number 245 (November 4, 1988).

experimental target areas which are typically shielded with at least 360 cm of heavy concrete over target caves. Based on these thicknesses, the AGS facilities are designed to achieve only a small fraction of the annual areal dose goal; i.e., the present shielding would allow at least 8 times more protons per year while satisfying the annual limit of 8.5×10^{9} rem-cm^{2} for this conservative calculation.

Not all protons will be stopped at the targets or well-defined loss points; some are lost during transport. The maximum level for a full fault dose rate was considered since the design goal of no more than 20 mrem per full-fault event in an uncontrolled area is to be adhered to. Typically, the shielding on the AGS Ring and the transport lines allows these areas to experience a maximum fault dose rate is less than 5 rem in 1 hour.

AtR

Skyshine, from normal injection operation and faults in the AtR line, was computed to be 0.003 mrem/yr at the closest occupied building, which is 1005S, and 0.0001 mrem/yr at the closest site boundary. Skyshine from the AtR beam dump during set-up and studies was found to be 1.9 mrem/yr at Thompson Road, which is posted as a Controlled Area during RHIC operations, 1.6 mrem/yr at the AtR power supply Building 1000P, 0.006 mrem/yr at Building 1005S and 0.00023 at the closest site boundary.

RHIC

Skyshine dose from routine RHIC operations at non-posted areas is negligible. Building 1005S would receive 0.0028 mrem/yr and the closest site boundary 0.0001 mrem/y. During machine setup and studies, conservatively computed doses are 0.006 mrem/yr at Building 1005S and 0.00023 mrem/yr at the closest site boundary.[78]

Both the collimators and beam stops are intended locations for beam loss. The Collider beam stops are located on either side of the 10 o'clock intersection region. They account for about 85% of the total loss of beam energy[79,80]. The dose equivalent to the closest site boundary from operation of these dumps is <0.5 mrem/year. The areas on the collider berm that are above the dumps are fenced and controlled as Radiation Areas to exclude non-radiation workers.

Skyshine from the operation of the dumps was computed to be 0.4 mrem/yr at William Floyd Parkway, the low occupied shortest off-site distance and about 1.3 mrem/yr to the closest onsite building, 1101, which is inside the Controlled Area.

The primary beam collimators are located on either side of the 8 o'clock intersection region. The dose calculation assumed that 20% of the beam in each ring interacts on the collimator and at most, 10% of the stored beam in an hour[81]. Because of the radiation levels on the berm following routine and faulted losses, the area is fenced to exclude non-radiation workers. The dose at William Floyd Parkway is <0.5 mrem/yr and to the nearest onsite building, 1101 is 0.55 mrem/yr.

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[78] AD/RHIC/RD-83, A. J. Stevens, Analysis of Radiation Levels Associated with Operation of the RHIC Transfer Line, December 1994.

[79] A. J. Stevens, AD/RHIC/RD-48, Radiation Environment and Induced Activity Near the RHIC Internal Beam Dump, November 1992.

[80] A. J. Stevens, Estimate of Dose Rate Close to the C-Dump Core from Induced Activity, August 8, 1995.

[81] A. J. Stevens, AD/RHIC/RD-113, Radiation Safety Issues Near Collimators, April 1997.

4.5.4. Oxygen Deficiency Hazards

OSHA defines an oxygen deficient atmosphere in 29CFR1910.146 as atmospheres containing less than 19.5% oxygen by volume. Normal atmospheres contain ~21% oxygen. Actual effects from oxygen deficient atmospheres do not begin until the concentration falls to ~17%. If a small number of workers are exposed to potential oxygen deficient atmospheres, it is cost effective to use conservative controls for protection. However, with large exposed populations it is necessary to better establish controls at an appropriate level. With too little control, the injury rate may be unacceptably high. With too much control, the cost of doing business is prohibitive.

Controls address two types of exposures: one where a known oxygen deficiency exists, the other in which an oxygen deficiency does not exist but there is a potential for its occurrence. A known oxygen deficiency could exist, for example, in a confined space in which sample results show <19.5% oxygen. Work planning would determine the controls needed to safely work in this space. Controls would include periodic atmospheric monitoring, self-contained breathing apparatus, ventilation and confined space permits. The premise for controlling the latter condition, a potential oxygen deficiency, is that the risk to workers should be no greater than risks in a general industry setting.

If exposure to reduced oxygen is stopped early enough, effects are reversible. If not, permanent central nervous system damage or death can result. Major effects hindering escape from the vicinity of an oxygen deficiency are disorientation and unconsciousness. For personnel actively working, unconsciousness occurs at ~13% oxygen. A person in the general area of a catastrophic release of an inert gas and not hurt by a pressure wave would be alerted to the escaping gas by the noise and, if a cryogenic gas, the cold. That person could out-walk the expanding inert-gas cloud by holding their breath and safely walking to the nearest exit.

The controls for potential oxygen deficiency are focused on the workers in the general area of the potential release, but not the immediate vicinity of the release point. The survival of individuals in the general area is highly probable because of the administrative and engineering controls, monitoring systems, and training.

For an unlikely scenario in which an individual is in the immediate vicinity of the equipment that failed at the time of failure, the affected individual would lose consciousness in seconds and probably not survive.

Training for workers includes the methods to become aware that a release of inert gas has occurred, escape methods and use of appropriate oxygen monitoring devices and escape packs. In addition to training on use of oxygen monitors and escape packs, ODH information is given in facility specific courses required of all employees and users. For example, see Collider Users Training, which covers ODH posting, the effects of oxygen deficiency, the ODH classification system, the ODH alarms and when and how to evacuate.

The following is a description of the graded approach methodology used to determine the controls necessary for areas having a potential for oxygen deficiency. It is recognized that these simplified methods cannot directly and quantitatively address the effects of the inert gas concentration gradients during transient release of the gas. The approach is to use a prescribed, simplified analysis to determine how an individual can have reasonable assurance that they are protected from a gas release. It treats the problem in a global way, by assuming homogenous mixing of the gas. For helium and lighter gases, this is not unreasonable. For heavier gasses, such as Tandem insulating gas, a spectrum of assumptions has been made bounding the cases for both homogenous mixing and no mixing. As already noted, individuals near the location of any release have higher likelihoods of injury or death. Thus a combination of the BNL SBMS ODH methods coupled with engineering judgment, assumptions on worker training, evacuation procedures and monitoring equipment are utilized in determining the controls needed to ensure an acceptably safe workplace.

The BNL SBMS models are used to determine the oxygen deficiency hazard (ODH) classification of a building. The SBMS is based on the Fermi ODH model. The Fermi Model is a prescribed method to determine the necessary level of hazard control for a building having the potential for oxygen deficiency. A graded approach is used to implement hazard controls as a function of the computed ODH fatality rate. The fatality rate is selected as the hazard index since death is the most important, non-reversible effect of exposure to oxygen deficiency. The average industrial fatality rate, $\sim 10^{-7}$/hr, is defined to be the fatality rate at which protective measures, other than training and postings are required.[82]

The fatality rate in the SBMS model is the product of two numbers. One quantity is the probability per hour of an initiating event causing an oxygen deficiency. The other quantity is found by estimating the minimum oxygen concentration during the transient, assuming instantaneous mixing of the air and inert gas in the building volume, and is represented by a factor between 0 and 1, see Figure 4.5.4.a. The computed fatality rate is then used to define the ODH class necessary to protect personnel.

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[82] T. Miller and P. Mazur, Oxygen Deficiency Hazards Associated with Liquefied Gas Systems: Derivation of a program of Controls, Am. Ind. Hyg. Assoc. J. 45(5):293-298(1984).

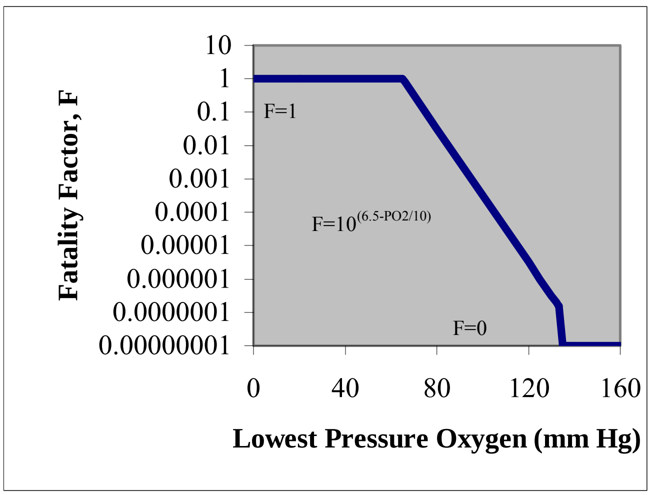
The ODH fatality rate is defined as:

$$\Phi = PF$$

where Φ = the ODH fatality rate per hour
P = the expected rate of the event per hour, i.e. initiator frequency
F = the fatality factor for the event, Figure 4.5.4.a

The value of P, the initiator frequency, is determined by using actual equipment failure rate data provided by Fermilab and by the Nuclear Regulatory Commission.

Figure 4.5.4.a. Graph of the Fatality Factor (logarithmic scale) versus the Computed Oxygen Partial Pressure.



The value of the fatality factor, F, is the probability that a fatality will result if a particular gas release occurs. Figure 4.5.4.a defines the relationship between the value of F and the computed oxygen partial pressure. The partial pressure is found by multiplying the mole fraction of oxygen in the building atmosphere by normal atmospheric pressure, 760 mm Hg. If the oxygen concentration is greater than 18%, about 137 mm Hg, then the value of F is defined to be zero. That is, all exposures above 18% are defined to be safe and do not contribute to fatality. If the oxygen concentration is 18%, then the value of F is defined to be 10^{-7}. At decreasing concentrations the value of F increases until, at some point, the probability of fatality becomes unity. That point is defined to be 8.8% oxygen, about 67 mm Hg, the concentration at which only one minute of consciousness is expected.

The computed value of Φ, the fatality rate, is then used to determine the ODH class of the building as follows:

ODH Class	Fatality Rate (per hour)
NA	$<10^{-9}$
0	$\geq 10^{-9}$ but $<10^{-7}$
1	$\geq 10^{-7}$ but $<10^{-5}$
2	$\geq 10^{-5}$ but $<10^{-3}$
3	$\geq 10^{-3}$ but $<10^{-1}$
4	$\geq 10^{-1}$

The oxygen concentration in the building during a release of inert gas is approximated by solving the following differential equations:

(a) If the exhaust fan is on and the spill rate of gas, R, is less than the exhaust fan capacity, Q:

$$V\frac{dC}{dt} = 0.21(Q - R) - QC$$

Where

V = building volume, ft^3
C = oxygen concentration, mole or volume fraction
t = time, minutes
Q = exhaust fan(s) flow rate, CFM
R = helium spill rate into building, CFM

(b) If the exhaust fan is off or if the gas spill rate, R, is greater than the exhaust fan capacity, Q:

$$V\frac{dC}{dt} = -RC$$

Areas of the facilities which have potential ODH hazards have been evaluated as described above. Oxygen concentration alarm points vary from 19.5% to 18%, depending upon the location. Alarms set points below 19.5% are acceptable because these alarms warn of accidents and not of planned, routine working conditions. The results for the affected areas of the facilities are summarized in the following sections.

Tandem

The Tandem Van de Graaff has an inventory of insulating gas (45% sulfur hexafluoride, 45% nitrogen and 10 % carbon dioxide) used to insulate the accelerator tanks. During operation, each tank contains 11,250 ft^3 of gas at 180 psig. This is ~35,000 lbm or 160,000 ft^3 at atmospheric pressure. The gas has a specific gravity of about 2.85 and a low diffusion rate in air. The hazards and controls in place for this gas are described and evaluated in a detailed calculation of the various potential release locations during gas transfer and normal operations.[83] The evaluation included the Tandem accelerator room, mechanical equipment room, electrical equipment room, target rooms, basement, TtB tunnel and the remote gas storage area located south of Building 703. The analyses included the potential effect of the heavier than air insulating gas by examining different cases of mixing of the gas with the surrounding air, from no mixing to complete mixing with the affected room volume. Recommended upgrades were

[83] L. Snydstrup, Calculation of Oxygen Deficiency Hazards for TVDG, Revision 0, November 5, 2001.

completed to assure that all locations within the Tandem and the gas storage area are classified no higher than ODH 0.

g-2 Experiment

This experiment is currently not used but when it ran ODH hazards were involved. Details of ODH and controls will be added to the SAD if this experiment is restarted.

RHIC

Mechanisms exist which could result in the release of helium into the Collider Tunnel, Service/Support Buildings housing valve boxes and associated cryogenic system equipment, and the buildings housing the refrigerators and helium compressors. As shown in Table 4.5.4.a, there also is the potential for the release of nitrogen into certain buildings. The quantity and release rate for each gas at each location is dependent upon many variables. Postulated worst-case, peak release rates are presented in Table 4.5.4.a, along with building volumes and ventilation rates. This table shows that the inert gas release rates can exceed the ventilation rates, thereby displacing air. Likewise, failure of the ventilation system will rapidly cause a hazardous level of air displacement. Table 4.5.4.a has notes that explain the major assumptions of the calculations.[84,85,86]

For the refrigerator building, an ODH 1 hazard class condition occurs after about 8 minutes with both ODH fans on and 5 minutes with one fan on. This is adequate time for an individual to egress following an alarm; however the building is conservatively classified as ODH 1.

[84] R. Karol, Collider Building ODH Calculations – Revisited, April 18, 2000 (Revised 5/26/00).
[85] R. Karol, Building 1005E ODH Classification (Revised), December 26, 2001 (Revised May 6, 2002).
[86] R. Karol, Building 1006B Classification with Helium Reliquifier Running, September 20, 2002.

Some of the Service/Support buildings do not need controls; however, an ODH 0 is specified to uniformly apply ODH awareness and controls at the Collider.

The Helium Reliquifier components are located in buildings 1005E and 1006B. When this system is operating, calculations have shown that Building 1006B must be upgraded from ODH 0 to ODH 1 if only one exhaust fan is operable. Building 1005E requires two of the three exhaust fans to be operable to maintain an ODH 0 posting.

With the 80K Cooler on during Collider shutdown periods, the Tunnel and Service/Support Buildings are posted ODH 0 so that exhaust fans and oxygen sensors may be taken out of service without the need to keep track of the postings and to prevent confusion.

Helium spill tests, both at high and low release rates, were conducted to determine the helium gas temperature below which automatic ODH controls are required at the Collider.[87] It was concluded that the lowest temperature at which controls must be operable to protect personnel and maintain the ODH Hazard Class at the levels shown in Table 4.5.4.a is 50K. Above 50K, because of the decrease in helium density, the helium release rate would be less than 10% of the release rate at operating temperature of 4K. The areas need to be posted as soon as the helium system begins operation, but the oxygen sensors and ODH exhaust fans, which are part of the PASS, need only be operable when the helium temperature decreases to 50K.

[87] Relativistic Heavy Ion Collider Safety Assessment Document, October 1999. Chapter 4, Section A.6.

Table 4.5.4.a - ODH Classification for Collider Buildings

Building No.	Name	Bldg. Vol (ft^3)	Total Fan CFM (# Fans)	Peak He (N_2) CFM	Frequency[(1)] (per hr)	ODH Class/Fatality Rate (Φ) Case A[(4)]	Case B[(5)]
1005H	Compressor Building	250,000	100,000 (4 fans)	8,000[(note 2)] (1500)	$3x10^{-5}$	NA / note 6	NA / note 6
1005R	Refrigerator Building	240,000	50,000 (2 fans)	27,000[(note 2)]	$3x10^{-5}$	1 / note 7	1 / note 7
1005E	Reliquifier Building	30,000	10,000 (2 fans)	(5,000[(note 2)])	$5.9x10^{-3}$	0 / 2 x 10^{-8}/hr	0 / note 7
1001	Collider Tunnel - 1:00	310,000	60,000 (3 fans)	157,800[(note 3)]	$1.2x10^{-5}$	NA / note 8	0 / note 8
1003	Collider Tunnel - 3:00	300,000	60,000 (3 fans)	157,800[(note 3)]	$1.2x10^{-5}$	NA / $1x10^{-10}$	0 / $1.9x10^{-9}$
1005	Collider Tunnel - 5:00	390,000	60,000 (3 fans)	157,800[(note 3)]	$1.2x10^{-5}$	NA / note 8	0 / note 8
1007	Collider Tunnel - 7:00	400,000	60,000 (3 fans)	157,800[(note 3)]	$1.2x10^{-5}$	NA / note 8	0 / note 8
1009	Collider Tunnel - 9:00	320,000	60,000 (3 fans)	157,800[(note 3)]	$1.2x10^{-5}$	NA / note 8	0 / note 8
1011	Collider Tunnel - 11:00	300,000	60,000 (3 fans)	157,800[(note 3)]	$1.2x10^{-5}$	NA / $1x10^{-10}$	0 / $1.9x10^{-9}$
1002B	2:00 Support Building	70,000	32,000 (2 fans)	17,000	$3x10^{-6}$	NA / $1x10^{-10}$	0 / $1.1x10^{-8}$
1004B	4:00 Support Building	113,000	44,000 (2 fans)	17,000	$3x10^{-6}$	NA / $3x10^{-12}$	0 / $5.2x10^{-11}$
1006B	6:00 Support Building	85,000	32,000 (2 fans)	17,000 (12,000[(note 2)])	$3x10^{-6}$	NA / $4.1x10^{-11}$	0 / $2x10^{-9}$
1008B	8:00 Support Building	75,000	32,000 (2 fans)	17,000	$3x10^{-6}$	NA / $7.4x10^{-11}$	0 / $5.9x10^{-9}$
1010A	10:00 Support Building	110,000	22,000 (2 fans)	17,000	$3x10^{-6}$	NA / $6.1x10^{-11}$	0 / $8.6x10^{-10}$
1012A	12:00 Support Building	110,000	22,000 (2 fans)	17,000	$3x10^{-6}$	NA / $6.1x10^{-11}$	0 / $8.6x10^{-10}$

Notes:

(1) Frequency is given as the probability per hour that the bounding helium or nitrogen system failure occurs within the building.

(2) Conservatively assumed to be constant at these helium spill values for 1005H and 1005R and for nitrogen in 1005E and 1006B. The minimum ODH Class for the Compressor Building is conservatively set at ODH 0 due to the inventory of the helium present in the building and in order to simplify ODH controls.

(3) Peak helium spill rate obtained from AD/RHIC/RD-79, Estimation of Helium Discharge Rates for RHIC ODH Calculations, September 1995.

(4) Case A assumed all building fans operational. The minimum ODH Class for the Tunnel Sextants and the Support Buildings is conservatively set at ODH 0 due to the inventory of helium present in the buildings and in order to simplify ODH controls.

(5) Case B considers one fan failed. The ODH Class for all Support Buildings is based on the worst case to simplify ODH controls.

(6) For the Compressor Building, the oxygen concentration will only fall to a minimum of 18.8%. The minimum ODH Class for the Compressor Building is conservatively set at ODH 0 due to the inventory of the helium present in the building and in order to simplify ODH controls.

(7) For the Refrigerator Building and Reliquifier Building, the time to ODH 1 was determined ($\Phi = 10^{-7}$). See text for description.

(8) Tunnel Sextants 1003 and 1011 bound the conditions for all sextants because they have the smallest volumes.

4.5.5. Electrical Hazards

Chapter 3 and previous SAD revisions of C-AD owned accelerators, experiments and the Collider, describe in detail the numerous electrical devices, magnets, power supplies, vacuum system, RF systems, beam instrumentation and controls, that are employed at C-AD facilities including accelerators and experiments.

The sheer number of electrical devices and their conductors installed at accelerator and experimental facilities justifies recognizing electrical hazards as a major personnel hazard which requires detailed hazard controls. C-AD adheres to BNL SBMS, ES&H Standards 1.5.0 through 1.5.2 in order to mitigate electrical hazards. The hazards are described as follows:

AC Distribution

a) The primary AC distribution is at 13.8 kV. The feeds are underground to substations located at various sites. Transformers convert the 13.8 kV to 480 volts ac for subsequent distribution. Because of the very high hazard, the substations are fenced in with controlled access by the BNL Plant Engineering personnel. C-AD personnel do not normally have access to these areas.

b) Most secondary distribution is 480 V, 3 phase, 60 Hertz, ungrounded delta. This is used directly in many pieces of equipment, motors, pumps, power supplies, etc. It is further transformed to 220/120 V, 3 phase for lights, utility outlets and all general needs. Substations at Buildings 1005S and 1005H have grounded wye which is further transformed to 208/120 V. The RHIC tunnel lighting is 277 V which is fed from 480 V to 480/277 V isolation transformers to reduce the fault current magnitude. The 480/277 V neutral is grounded. There are two 4160 V substations at Building 1005H to power the helium compressors. Substations A-500, Q and 925 are also grounded wyes. The hazard at 480 V is not only from a 480 V shock, but also from the possible arc formation at a short circuit. The short circuit currents are extremely high and an arc can spray molten copper and other materials. The procedures followed on 480 V circuits include training, LOTO or key lockout, circuit voltage testing, and the use of proper personnel protective equipment.

High Voltage, Direct Current

a) Low Current - In many pieces of electronic equipment there are high voltage, low current, power supplies. While the current in some cases may present a direct shock hazard, in others it will be too low to cause a direct injury, but may lead to indirect injuries, such as, falls, bumps or other physical or electrical mishaps. Accelerator and experimental components are prominently marked for a high voltage hazard and may also be interlocked if a direct shock hazard exists. Experimenter's equipment use high voltage power supplies and each experimental set-up is reviewed by the ESRC before being energized.

b) High Current - In the range of 10-50 mA passing through the body significant physical harm may occur. The rf systems, as well as various pulsed magnets, kickers, and other devices, use potentially lethal power supplies. All such power supplies are properly marked; interlocks actuated on entry to the supply are hard wired to the power source; panel indicator lights show the power supply status; local-remote lockout switches are provided where more than one turn on location is used. Shorting devices are provided, manual or automatic, especially on capacitor storage devices.

High Current, Low Voltage

Many devices use high currents, up to several thousand amperes, at relatively low voltages. In most cases the shock hazards are low but a short circuit on the lines, just as in the 480 V ac case, can create a physical hazard. Proper warnings, enclosing of conductors and interlock devices are used.

RF Voltages

RF voltages in the many kilovolt level are present in the accelerating systems. Contact can result in shock and deep rf burns. The procedures as in the high voltage DC case are used.

4.5.6. Fire Hazards

The primary combustible loading in the injectors, accelerators, collider and experiments consists of magnets, power and control cables, and beam diagnostic equipment located throughout the complex. None of the materials is highly flammable, and with the possible exception of small amounts of control cable, all are expected to self-extinguish upon the de-energizing of electric power. Small amounts of flammable materials are routinely used in support of the accelerator operations and experiments.

Due to a system for diversion of radioactive liquid effluent to a hold-up pond, there are no environmental impacts due to release of contaminated water from the fire protection water system. Water sprayed on radioactive equipment may become slightly contaminated but would enter the sanitary system and be monitored before release. There are no significant amounts of combustible activated materials in the tunnels, rings, transport lines, intersection regions or beam lines and no significant radioactive particles would be present in smoke. Thus, there is no significant environmental hazard from a fire at the C-AD facilities.

At times, liquid hydrogen targets may be used in Building 912 for the experimental program. The danger of an over-pressure associated with a deflagration of hydrogen from such a target is about 17 lbs of TNT equivalent. The over-pressure wave is such that it will be lethal to anyone within a 30-foot radius. There is no full-time occupancy within this zone and equipment racks and monitoring stations are typically more than 30 feet away. These zones are maintained as low-occupancy areas. Experimenters and watch personnel may walk by or briefly work in the zone; typically, one or two people at a time. Flying debris will pose an additional threat. The peak over-pressures are likely to be significant to move large magnets nearby, collapse the target enclosure and collapse nearby experimental detectors. The nearby secondary beam dumps will likely remain standing.

The experiments at the Collider contain larger volumes of flammable gases in their detectors. Details of the hazards associated with these systems are presented in Chapter 4 of the original RHIC SAD. To mitigate these fire hazards the experimental detectors have mechanical and electrical interlocks, flow restrictors, designs to industry codes and standards, fusing, over and under flammable gas pressure protection, flammable gas detection, limits on flammable gas volumes, fire detection, alarm and suppression systems, control of combustible loading, ventilation systems, safety committee reviews, experimenter training for emergencies, automatic inert gas purging systems, control of ignition sources, and enhanced work planning.

4.5.7. Hazard Controls

The purpose of this section is to briefly summarize the various system features and administrative programs that help to control hazards or the minimize risk of various hazards.

Radiation Protection

The significant hazard at the C-AD facilities is ionizing radiation, and operations are planned to be within DOE dose guidelines. The Department uses a graded system of controls such as shields, fences or barriers, locked gates, interlocks and procedures to match access restrictions with potential radiation hazards that satisfies both the BNL and DOE requirements.

Although the Laboratory site is a limited access site, service personnel from off-site or BNL non-radiation workers may work near C-AD facilities or may traverse the complex. The BNL policy is to administratively restrict the dose to 25 mrem per year to such personnel. The C-A Department adheres to this policy by using shielding, radiation monitoring devices that prevent radiation levels from exceeding set points, radiation work permits, work planning and RS LOTO.

Shielding for C-AD facilities is also designed to permit access by appropriately trained personnel to areas adjacent to the beam enclosures even with nominal inadvertent beam loss. In locations where the losses are expected to be greater, such as outside the shielding near collimators or the beam stops, physical barriers such as fences are used to control access and minimize exposures. Depending on the area classification, these barriers may be locked and/or posted as Controlled Area, Radiation Area or High Radiation Area.

There is the potential of significant residual activity in several locations, which are targets, collimators, injection regions, and beam dumps. To work near these locations, movable shielding may be brought into place using the remote capabilities such as a crane or a fork truck. This minimizes the potential integrated person-dose for work done within the beam enclosure.

Permanent Shielding and ALARA Dose

Shielding will be used to reduce radiation levels in occupied areas to acceptable levels. The C-A Department's shielding policy is given in Appendix 3. Potential access points into areas where personnel are prohibited during operations will be controlled by the Access Control System, ACS and PASS.

Shielding design analyses were performed for all sections of C-AD facilities, and ALARA was integrated into the overall facility designs. Soon after beam is available, studies are conducted in order to verify the design and to optimize shielding, as needed, to help achieve an ALARA dose to facility personnel and facility users. Extensive radiation surveys of normal operations, as well as low-intensity simulated, credible beam faults, are conducted as required during commissioning and initial operations of new portions of the facility or experiments. These surveys provide assurance and verification of the adequacy of the shielding and access controls. It is noted that the permanent shielding and access controls are configured to support the BNL Radiation Control Manual dose limit requirements, and are further enhanced to support the BNL Radiation Control Manual ALARA considerations.

The shield was planned with ALARA in mind such that, during normal operations, the dose rate on accessible outside surfaces of the shield is planned to be less than 0.25 mrem/h in areas under access control. Areas under access control are all designated Controlled Areas or radiological areas as defined in the BNL Radiation Control Manual. The design of 0.25 mrem/hr is a guideline based on the actual ALARA design objective of less than 500 mrem per year. That is, assuming 100% occupancy at the shield face, a 2000-hour per year residence time yields an acceptable ALARA design objective of 500 mrem. The 500 mrem per year ALARA design objective is one half the design objective stated in 10CFR835 § 835.1002 (b).

Since there are many ways to control access and residence time by area designation, training, signage and work planning and since there is a decrease of dose rate with distance from the shield face, significantly higher shield face dose rates are often acceptable. Therefore, shields are evaluated in terms of the guideline of 0.25 mrem/h, and instances where higher values may be acceptable have postings to indicate where area designations play a major role in minimizing radiation exposures.

Permanent Shielding Materials

The permanent bulk shielding materials for the C-AD facilities are primarily materials used at all existing accelerator facilities. For example, concrete, iron and earth provide protection for personnel outside the beam tunnels, target stations and beam intersecting regions. In addition, in order to satisfy the BNL capping requirements, the berms which surround significant beam loss locations are covered with caps to prevent leaching of soil activation products, tritium and sodium-22, from contaminating the groundwater. In addition to the materials mentioned above, paraffin, borated paraffin, polyethylene, borated polyethylene, lead and depleted uranium[88] may be used for local shielding and in special circumstances. Shielding configuration is closely controlled and may not be changed without review and approval of the C-A Radiation Safety Committee (RSC).

[88] Implementation Plan and Basis for Interim Operation (w/PHA) AGS Uranium Shield Block and Experiment 877 Uranium Calorimeters.

Radiation Detection and Radiation Interlocks

At locations external and/or adjacent to beam enclosures where unlikely but possible beam loss may occur, the use of hard-wired, fail-safe interlocking radiation monitors are used. This technique is standard practice at DOE accelerator facilities to maintain radiological-area classification compliance by providing a robust and rapid beam inhibit if any monitor exceeds a preset interlock limit. These radiation monitors are part of the QA level A1 safety-significant access-control-system for personnel protection.

Interlocking radiation monitors are calibrated annually. These radiation monitors have been dubbed Chipmunks. They are tissue-equivalent ionization chambers that measure dose equivalent rate, in mrem per hour, from pulsed, mixed-field neutron and gamma radiation. Chipmunks are used as area-radiation monitors for personnel protection and are located throughout the facility in accessible areas. Chipmunks are used to interlock the ion beams should radiation levels exceed limits defined by the C-A Radiation Safety Committee. The operation of Chipmunks with interlocking capability is fail-safe. Loss of power results in beam off for interlocked Chipmunks, and/or an alarm in the Main Control Room in Building 911A, a control room that is manned around-the-clock during operations. Additionally, the Chipmunk uses a built-in keep-alive radiation source to monitor for failures. Such a failure will trigger an alarm in the Main Control Room and/or an interlock when appropriate.

The interlock system is hard-wired and uses relay logic and PLCs to activate or deactivate a device such as a beam stop or magnet power supply to prevent beam from entering the fault area when a fault condition is detected. The PLC systems are monitored by an independent computer, and the fault condition is logged.

Fixed-location area-radiation monitors such as Chipmunks also provide real-time dose information at various locations along the beam path and in the target, support and experimental buildings. This dose rate data is logged every few minutes and stored on computers. General locations are initially selected for the real-time monitors; exact locations are determined based on beam-loss tests conducted during the facility commissioning phase and on subsequent radiation surveys during operation. Final area radiation monitoring instrument locations are approved by the C-A Radiation Safety Committee.

Additional area monitors may be used to assess the long-term integrated dose in areas accessible to the public and other individuals not wearing personnel dosimeters. Thermo-luminescent dosimeters (TLDs) identical to those worn by radiation workers are mounted in locations in accordance with the BNL Radiological Controls Division procedures for this purpose. The dose recorded by these TLDs is indicative of the exposure of a person spending full time at that location. Neutron dosimeters, if their use is indicated for this purpose, will be attached to phantoms to simulate use by personnel.

Control of Radioactive Materials and Sources

When the beam is turned off, the remaining radiation hazard comes from activated material and sources. Activated material may be a direct radiation hazard, and may have removable contamination. All known or potentially activated items will be treated as radioactive material and handled in accordance with BNL Radiation Control Manual requirements. Unlabeled radioactive material that is accessible to personnel is placed in appropriately posted radiological area. Suspect radioactive material is surveyed by a qualified RCT before release and then controlled in accordance with the survey results. Process knowledge may also be used to certify items being removed from radiological areas as being free of radioactivity. Known radioactive materials are appropriately labeled before removal from an area that is posted and controlled. Radioactive items with removable contamination on accessible surfaces are packaged before removal from posted radiological areas. Workers whose job assignment involves working with radioactive materials receive documented training as radiological workers. Radioactive sources below accountable-activity-limits are treated as radioactive material. Accountable sealed radioactive sources are controlled, labeled and handled in accordance with the BNL Radiation Control Manual and the C-A Operations Procedure Manual. Accountable sealed radioactive sources that are in regular use are inventoried and leak-tested every six months.

Portable Radiation Monitors

Portable radiation detection instruments are used by Radiological Control Technicians (RCTs) and, potentially, other trained and approved C-A personnel, to measure the radiation fields in occupied areas during commissioning and periodically during normal operations. These measurements will be used to establish and confirm area radiological postings. Instruments used for this purpose will be appropriate for the type and energy of the expected radiation, and will be calibrated in accordance with requirements.

Frisking Instruments

Experience at the C-AD accelerators and experiments have shown that contamination is not a significant problem at our facilities. However, routine contamination surveys are conducted to verify that contamination is not a problem. Instruments used to frisk personnel who are exiting posted areas that might contain removable contamination are used as appropriate.

Personnel Dosimetry

All radiation workers wear appropriate TLDs and self-reading dosimeters as required by the BNL Radiation Control Manual while working in areas posted for radiation hazards. Dosimeters are exchanged on a regular basis and processed by a DOELAP-accredited laboratory. Records of the doses recorded by these dosimeters are maintained, and these records are available to the monitored individuals.

Access Controls Systems

The radiation security system design for access controls at C-A facilities has operation for over 43 years. The C-A Department has classified the security system as

QA level A1 according to the C-A QA plan, but the Department allows certain components to have a lower classification because failure is to a safe state or critical parts are redundant. The Access Controls Group installs industrial grade components only. This Group labels parts that pass incoming tests as A1 or A2 and places labeled parts in controlled storage areas. The Group maintains documentation for these acceptance tests.

The basic design principles of the access control system are:

- either the beam is disabled or the related security area is secured
- only wires, switches, relays, PLCs and active fail-safe devices, such as chipmunks, are used in the critical circuits of the system
- the de-energized state of the relay is the interlock status; that is, the system is fail-safe
- areas where radiation levels can be greater than 50 rem/h require redundancy in disabling the beam and in securing the radiation area
- if a beam fails to be disabled as required by the state of its related security area, then the upstream beam would be disabled; that is, the system has backup or reach-back

Very High Radiation Areas are those areas that enclose primary beam. Very High Radiation Area hardware requirements comply with the BNL Radiation Control Manual. The C-A Radiation Safety Committee requires: 1) locked gates with two independent interlock systems, 2) fail safe and redundant radiation monitors or other sensing devices, 3) indicators of status at the facility in the Main Control Room, 4) warning of status change, and 5) emergency stop devices within potential Very High Radiation Areas.

The C-A Radiation Safety Committee reviews interlock systems for compliance with requirements in the BNL Radiation Control Manual, Standards Based Management System requirements and C-A Operations Procedure Manual procedures. A

Representative of the BNL Radiological Controls Division is a member of the C-A Radiation Safety Committee. The C-A Radiation Safety Committee defines the design objectives of the security system and approves the logic diagrams for relay-based circuits and state tables for PLC-based circuits. Cognizant engineers sign-off on wiring diagrams and the C-A Chief Electrical Engineer approves each diagram. The C-A Access Controls Group maintains design documentation.

The Access Controls Group conducts a complete functional check of all security system components at an interval required by the BNL Radiological Control Manual. In the checkout, the Access Controls Group checks the status of each door-switch on a gate, and each crash switch in the circuit. They check the interlocks and the off conditions for all security-related power-supplies to magnets, magnets that may act as beam switches, and for all security-related beam-stops. They check every component in a security circuit. As they test, they fill-out, initial and date the security system test-sheets obtained from the C-A Operations Procedure Manual. Test records are maintained as required by the C-A Operations Procedure Manual.

Control and Use of Hazardous Materials

The BNL Chemical Management System is designed to ensure that workers are informed about the chemical hazards in their workplace. The Chemical Management System is maintained to comply with OSHA and EPA regulations concerning hazardous chemical communications. This program includes provisions for policy, training, monitoring exposure limits, handling, storing, and labeling and equipment design, as they apply to hazardous materials. Inclusive in the hazardous material protection program will be: procurement, usage, storing, inventory, access to the hazardous materials, as well as housekeeping and chemical hygiene inspections of C-AD facilities. All BNL general employees receive appropriate general Hazard Communication training. Standards for general hazardous materials communication and for special materials, such as beryllium, mercury and biological materials are specified by the BNL Standards Based Management System. Training to these standards is provided, and the training program records are maintained on the BNL BTMS. C-AD staff and experimenters working in areas with a potential for exposure to hazardous chemicals receive appropriate job-specific training at the time of initial assignment and whenever a new hazard is introduced into the work area. A comprehensive listing of all Materials Safety Data Sheets for the chemicals used at the BNL site is available on the BNL web or equivalent. The system of work controls, which is part of the BNL Integrated Safety Management System, requires enhanced work planning for work with certain hazardous materials; for example, beryllium. The enhanced work planning ensures that adequate hazard controls and completion of required training are in place before work with hazardous materials begins.

The use of flammable liquids is minimal. For example, the anticipated use at NSRL is less that one quart in each laboratory space as a solvent. Any use of flammable liquids follows BNL ES&H Standards / SBMS requirements.

Electrical Safety

The requirements for electrical safety are given in detail in the BNL Standards Based Management System and the C-A Operations Procedures Manual. Electrical bus work is covered to reduce/prevent electrical hazards in the power supply areas. In beam enclosure areas, exposed conductors will not be present and magnet buss will be covered. The Main Control Room will lock out all power supplies that power devices inside a beam enclosure whenever the area is placed in Restricted Access mode. In Controlled Access mode, even though the magnets will not be powered, the power supplies will not be locked out. Workers are trained to assume that magnets are powered in all cases and to treat them accordingly. In cases where workers are required to work on or near a specific magnet during Controlled Access or Restricted Access, the magnet power supply will be locked out and tagged out by the worker.

In some cases, it will be necessary to work near magnetic elements while powered. Appropriate control over access during this mode is maintained by the Operations Coordinator. Work planning, Working Hot Permits and training requirements for entrants under these circumstances address concerns for inadvertent contact with powered conductors and exposure to magnetic fields.

Lockout/Tagout Program

Lockout/tagout procedures are specified in the C-A Operations Procedure Manual. All workers will be required to train in lockout/tagout procedures at a level consistent with their position. Where electrical hazards could be present to C-A personnel working in an area, lockout/tagout procedures are implemented only by trained and authorized personnel.

Safety Reviews and Committees

Standing safety committees are utilized throughout design, construction, commissioning and operation to focus expertise on safety, environmental protection, pollution prevention and to help maintain configuration control. See Chapter 3 for details of each committee's authority and responsibility.

Training

Worker training and qualification is an important part of the overall ESH plan for C-A Department. Training and qualification of workers is described in the Operations Procedures Manual and the required training for individuals is defined in the Brookhaven Training Management System (BTMS). All staff personnel and experimenters require an appropriate level of training to ensure their familiarity with possible hazards and emergency conditions.

Workers are trained in radiation and conventional safety procedures at a level consistent with their positions. The number and type of training sessions/modules is assigned using a graded approach commensurate with the staff members' responsibilities, work areas, level of access, etc. An up-to-date record of worker training will be kept in the BTMS database. Radiation worker access will only be allowed if adequate training is documented, except in cases of emergency. Training procedures and course documentation will be reviewed and updated periodically.

Personal Protective Equipment

Special clothing is used to protect workers who are exposed to the various electrical hazards and hazardous materials, including chemicals and radiation. The clothing for a particular application is selected considering the expected hazards; a variety of types of clothing is needed to meet all hazards. There are no predicted hazards that are unique to C-A facilities, and experience is applied to ensure the adequacy of protective clothing in a particular application.

Respiratory protection is provided for workers who might otherwise be exposed to unacceptable levels of airborne hazardous materials, including chemicals, oxygen deficient atmospheres and radioactive materials. Respiratory protection is selected, used and maintained per OSHA 29CFR1910.134 and BNL Respiratory Protection Procedures.

4.5.8. Significant Environmental Aspects and Impacts

In support of Brookhaven National Laboratory's broad mission of providing excellent science and advanced technology in a safe, environmentally responsible manner, the Collider-Accelerator Department is committed to excellence in environmental responsibility and safety in all C-A Department operations.

To provide excellent science and advanced technology in a safe and environmentally responsible manner the Collider-Accelerator has, over the past 15 years, continuously reviewed the aspects of its operations in an effort to identify and accomplish waste minimization and pollution prevention opportunities. This process began in 1988 with the development of formal environmental design guides and a design review process. More recently, this effort has resulted in a further formalization of its processes under the guidelines of ISO 14001, the BNL ISO 14001 "Plus" Environmental Management System Manual, and SBMS subject areas governing ISO 14001 implementation. The BNL EMS program emphasizes compliance, pollution prevention and community outreach. Based on the aspect identification and analysis process in the Subject Area, Identification of Significant Environmental Aspects and Impacts, the following aspects are significant to the C-AD activities:

- regulated industrial waste
- hazardous waste
- radioactive waste
- atmospheric discharge
- liquid effluents
- storage/use of chemicals or radioactive material
- soil activation
- PCBs
- environmental noise
- water consumption
- power consumption

The environmental policy as set forth by Brookhaven National Laboratory in the Environmental Stewardship Policy is the foundation on which the C-A Department manages significant environmental aspects and impacts. The formal management program is called the C-A Environmental Management System. The Environmental Management System consists of the following elements, the details of which may be found in the C-A Operations Procedure Manual:[89]

- environmental policy
- planning
- environmental aspects and impacts
- system for determining legal and other requirements
- system for defining objectives and targets
- environmental management programs
- implementation and operation
- structure and responsibility
- training, awareness, and competence
- communication
- environmental management system documentation
- document control
- operational control
- emergency preparedness and response
- checking and corrective action
- monitoring and measurement

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[89] http://www.rhichome.bnl.gov/AGS/Accel/SND/OPM/Ch01/01-10-02.PDF Environmental Management Program Description

- nonconformance and corrective and preventive action
- records management
- environmental management system audit
- management review

The requirement for a process evaluation is listed in C-A OPM Chapter 13. Waste streams are reviewed by the C-AD Environmental Compliance Representative (ECR) and a process evaluation denoting all material inputs and outputs for the each process is on file for existing processes. A new process evaluation is performed for each new, significant process before commissioning the new facility for operations.

4.5.9. Hazard Reduction Associated With Waste Generation and Handling

Hazards associated with handling, packaging, treating and disposing of wastes generated during operation and modification of the facility are reduced when the generation of these wastes is minimized via pollution prevention (P2) techniques. The BNL approach to P2 associated with the operation and modification of accelerators and experiments is to address it during the design and construction phase. The objective is to minimize or eliminate the anticipated costs associated with hazardous and mixed waste generation as well as the treatment and disposal of wastes and the consumption of resources in all facility life cycle phases: construction, operation, closure and decommissioning. Dollars spent during the design phases will provide for significantly reduced total costs over the life of the facility thus making more funds available for science. The following are the main objectives of the BNL P2 program:

- minimize the amount of hazardous, radioactive and mixed wastes that are generated
- minimize the cost of waste management
- comply with federal, state and local laws, executive orders and DOE orders

The Collider-Accelerator Department has implemented a P2 program as part of its commitment to comply with the Environmental Management System and ISO 14001. C-AD facilities have been registered to the ISO standard by a third party registrar since CY 2000. A number of lessons learned in this area from other BNL operations are incorporated into C-A operations. Modifications to C-A operations have helped minimize hazards and costs associated with the generation of waste streams.

4.5.10. Fire Detection, Egress, Suppression and Response

The basis of design for fire detection, egress, suppression and response has been determined in the individual fire hazard analysis (FHA). FHAs are on the C-AD web. C-AD facilities comply with DOE fire protection guidelines as well as NFPAs. The system is integrated with the site-wide system and is comprised of an automatic fire detection and suppression system that includes automatic fire suppression and rapid response capability coverage by the BNL Fire Department. Sprinklers are provided at the building ceiling or roof levels, intermediate levels and at or within enclosures, as required. Because of the low flammability of the magnets, power and control cables and beam diagnostic equipment in the tunnels and rings, they do not have automatic fire suppression systems, except for certain areas. They do have fire standpipes. Manual and automatic fire detection and alarm initiation devices are installed throughout the facility.

Where needed, smoke and/or heat detection devices are supplemented with pressure sensitive sensors, flammable gas detectors or other advanced detection devices such as high sensitivity smoke detection, HSSD. The appropriate portable fire extinguishers are provided for manual fire fighting efforts by trained staff. Fire alarms are alarmed at the BNL Fire Department, Building 599, and at BNL Police Headquarters, Building 50, thus providing continuous coverage for rapid fire response. This will put additional professional fire fighting resources into action within a short period. Roadways around the facility help protect it from surrounding wildfires. The building roofs are non-combustible metal and do not ignite from burning ash from brush fires.

The means of egress for occupancies is in accordance with NFPA 101. Enclosure exhaust fans are located at tunnels and rings for rapid smoke removal.

4.5.11. Routine Credible Failures

Routine credible challenges to controls associated with worker and experimenter protection and with environmental protection are further detailed in Appendix 2.

Beam losses in C-A accelerators and experimental enclosures are sufficiently attenuated by the bulk shielding for expected routine operation. Adequate shielding is provided to meet requirements established by the Laboratory for permissible exposure to radiation workers, non-radiation trained workers and members of the public during normal machine operations. Present shielding designs reduce all normal radiation levels to well below the DOE ALARA guidelines.

Exposure to nearby facilities is less than 25 mrem per year and only a small fraction of 5 mrem per year at the site boundary, which are the Laboratory guidelines for radiation exposure for nearby facilities and the site boundary, respectively. Radiation exposure to maintenance workers is reduced through the design of equipment to simplify maintenance and the selection of materials to minimize failures. In particular, equipment at high loss points such as targets, beam dumps, collimators, beam injection and beam extraction points receive detailed examination to assure that radiation exposure received in passing and during the maintenance of these components is kept as low as reasonably achievable. Through such reviews, it is reasonable to expect that maintenance activities be controlled to maintain radiation exposures well within the DOE annual limits, limits that are 5 to 20 times higher than the ALARA guidelines.

There are no significant quantities of dispersible gaseous or liquid radioactive materials, except for the radioactivity induced in magnet cooling water. In primary beam-line areas where the cooling water might escape confinement, e.g., a hose break, water detection mats underneath the magnets alarm and alert the watch personnel. Watch personnel are trained to confine, clean up and report water spills to management. Experience indicates that up to several hundred gallons may leak onto the concrete floor. The concrete floors are impermeable. Spilled water is sampled before release to the appropriate waste stream or is allowed to safely evaporate in place. No off-site threats to the public are present.

4.5.12. Maximum Credible Accidents

This section describes the bounding analysis scenarios for credible C-A facility accidents.

Maximum Credible Beam Faults

Linac, Tandem, Booster, AGS and Fixed Target Experiments

Not all protons will be stopped at the targets or at well-defined loss locations; some may be lost during transport. The design goal of no more than 20 mrem per full-fault event in an uncontrolled area is met by the proper design of shielding and radiation monitoring and interlocking systems. Typically, the shielding on the transport lines allow these areas to be designated no more than a "High Radiation Area" during a full-fault event; that is, maximum dose rate during a fault is less than 5000 mrem in 1 hour. These areas are further protected by interlocking radiation monitors which turn off the radiation source within 9 seconds of detecting a fault condition. Thus, the design guideline of no more than 20 mrem per event in an uncontrolled area is satisfied through a combination of shielding, postings, radiation monitors and beam interlocks.

Based on archival operating records, beam faults occur when magnet power fails, beam tuning is improperly controlled or when beam-line components are misaligned and placed into the beam path. Operators in the Main Control Room detect the problem immediately upon radiation alarm trips and from the resultant interlocks which turn the beam off. Operators are trained to investigate these events according to written procedures, correct the problem if appropriate, record the event for management review, and to discontinue operations if appropriate. Given the length of these events, 9 seconds or less, and the frequency of these events, several times during an annual running period, off-site radiation impact is negligible.

Experience at C-AD shows that use of 1) thick shielding, 2) fences and barriers at the berm and other areas, 3) ALARA beam tuning procedures, 4) radiation alarms in MCR and procedures that call for response to radiation alarms are sufficient to protect personnel in locations not directly monitored by radiation monitors or “chipmunks”.

Based on the system for formal design review by C-AD Committees, formal BNL and C-AD training programs, formal C-AD operations procedures, formal C-AD quality assurance programs for equipment, and the extensive use of shielding and access controls, the probability of a "catastrophic" radiation exposure is extremely improbable, that is, the probability for this consequence cannot be distinguished from zero.

The use of radiation area monitors and interlocks to prevent high fault dose rates from occurring maintains exposures well within the limits established by DOE. Thus, the probability of a significant inadvertent radiation exposure is remote and is not likely to occur within the life cycle of the C-AD facilities. Routine maintenance and operations activities are well controlled and will not result in exceeding the annual radiation limits established by DOE.

RHIC

The RHIC Beam Loss Scenario assumes that an uncontrolled loss of a beam at full energy is possible at a location other than at the intended loss point, the Beam Stops at 10 o'clock. In the case of a bounding Collider fault with the ASE limited intensity proton beam, it is assumed that, for most locations in each ring, half the beam, the equivalent of 1.14×10^{13} 250 GeV protons, is lost at a point and the other half distributed over an extended length of magnets. The entire beam could be lost at an aperture-defining location including the high β quadruples. At the superconducting Tevetron at Fermi National Laboratory the entire full energy beam has been lost twice in approximately 10 years of running, but in both cases the loss was distributed over a long portion of the machine. The maximum credible loss defined here is therefore conservative. The maximum dose from a bounding fault to an individual standing at a typical location on the berm is estimated to be 57 mrem. This is within the 100 mrem regulatory dose limit for untrained individuals in uncontrolled areas. This fault is higher than the 20 mrem limit for all other C-A facilities because the entire stored beam in the Collider is lost at once, whereas at facilities other than the Collider, the beam is interlocked off within 9 seconds. During the commissioning and the first year of operation, the RHIC beam intensity was slowly increased, so that uncertainties in calculations of the dose potential could be determined by a series of fault studies. These fault studies were documented by Stevens[90]. Thus the maximum credible Collider fault has no adverse impact.

[90] A. J. Stevens, C-AD/ES&F Technical Note No. 156, Summary of Fault Study Results at RHIC, July 12, 2000.

Maximum Credible Fire

The objectives of presenting no threats to the public health and welfare or undue hazards to life from fire are satisfied. The designs of all C-A facilities comply with the "Life Safety Code" (NFPA 101) and with the specific requirements of the Occupational Safety and Health Standards (CFR29, Part 1910) applicable to exits and fire protection.

Welding gases and flammable/explosive gases used in experiments are used and stored according to NFPA codes and standards applicable to experimental installations. Gases are stored in compressed gas cylinders that meet DOT specifications. Large quantities of gas are forbidden in experimental areas, and experimenters are limited to using 100 to 200 lb cylinders during running periods. There are no off-site threats to the public should a cylinder fail.

Experiments are designed with an "improved risk" level of fire protection. The design requirements that were used are found in: 1) DOE Order 420.1, Facility Safety and 2) DOE Order 6430.1A, General Design Criteria. Experiments are fitted with fire detectors and fire protection systems where appropriate. Fires at experiments are expected to be extinguished by these protective systems. Combustible loading of the primary beam lines consists of magnets, power cables, control cables and beam diagnostic equipment. None of the materials are highly flammable, and with the possible exception of small amounts of control cable, all are expected to self extinguish upon de-energizing of electric power. Induced radioactivity is deeply entrapped in magnets and concrete shielding and is not dispersible in a fire. There are no off-site threats to the public from a fire.

The personnel risks associated with the fire hazard are acceptable considering the type of building construction, the available exits, the fire detection systems, the fire alarm systems and the relative fire-safety of the components and wiring. Emergency power and lighting is available in accordance with fire industry standards.

Travel distances to exits in the C-AD facilities do not present a problem. In structures of low or ordinary hazard and in structures used for general or special industrial occupancy, NFPA 101 permits travel distances up to 120 m to the nearest exit if the following provisions are provided in full:

- application is limited to one-story buildings only
- interior finish is limited to class a or b materials per NFPA definitions
- emergency lighting is provided
- automatic sprinklers are provided in accordance with NFPA 101
- extinguishing system is supervised

Smoke and heat venting by engineered means or by building configuration are provided to ensure that personnel are not overtaken by spread of fire or smoke within 1.8 m of floor level before they have time to reach exits.

DOE has established limits of $1,000,000 for a Maximum Possible Loss and $250,000 for a Maximum Credible Loss mandating the installation of automatic suppression systems in locations where those limits are exceeded. C-A facility designs meet these criteria.

The results of Fire Hazard Analyses for each major C-A facility are documented in the Appendices. These FHAs include the Maximum Possible Loss and Maximum Credible Loss for each facility.

Maximum Credible Electrical Accident

The electrical systems and equipment have been in use at C-A facilities for many years. This statement does not minimize the inherent dangers; rather, it indicates that the technical personnel are experienced on accelerator circuits and devices. Additionally, they are qualified to work on these systems. Every engineer, technician and electrician that is expected to work on the facility equipment is adequately trained. The training includes an awareness of potential hazards and knowledge of appropriate safety procedures and emergency response plans. Training is documented and a list of authorized personnel is kept on a network electronic database (BTMS) and available to supervisors.

The C-A staff is familiar with the types of electrical hazards that relate to the accelerators and experimental areas. All reasonable safety features are installed in and on the electrical equipment. The groups that maintain, repair, test and operate the equipment have the knowledge, tools and experience to perform safely. Work planning, which includes electrical safety procedures, working hot permits and job safety analyses, is done to adhere to the safe practices mandated by OSHA and the BNL SBMS Subject Area on Electrical Safety. Periodic retraining improves the safety margin. Thus, the potential risk for a serious electrical shock is minimized to levels currently accepted throughout the industry.

4.5.13. Risk Assessment to Workers, the Public and the Environment

Radiation Risks

The routine radiation dose to workers is well below the DOE regulatory limits of 10CFR835. The range of doses received by C-A radiation workers in CY2000, which was a typical recent year with full high-energy and nuclear physics programs, is shown in Figure 4.5.13.a. Experience shows the average exposure of C-A radiation workers is about 30 mrem per year. The dose to an average C-A radiation worker is only a small fraction of the regulatory limit, and the increase in fatal cancer risk after a lifetime of radiation work, 50 years, is insignificant, 0.06%[91] compared to the naturally occurring fatal cancer rate of nearly 20%. Additionally, due to increased emphasis on the nuclear physics program and due to improvements in high-intensity beam steering and confinement, the radiation burden for the C-A worker has been declining for decades. See Figure 4.5.13.b for the decline since the early 1990s. The risks to the public are an extremely small fraction of worker risk.

Worker doses, even including the maximum credible beam fault dose on a frequent basis, would not cause deterministic effects such as burns or tissue damage unless an individual were in the beam enclosure during operations. The Access Control System, which is categorized as Safety-Significant, assures that such irradiations are not credible.

[91] This assumes a risk coefficient of $4x10^{-4}$ per rem for workers from NCRP Report No. 115, Risk Estimates for Radiation Protection (p. 112) and a 50-year career at 30 mrem per year.

Figure 4.5.13.a Range of Radiation Worker Dose at C-A Department for CY2000

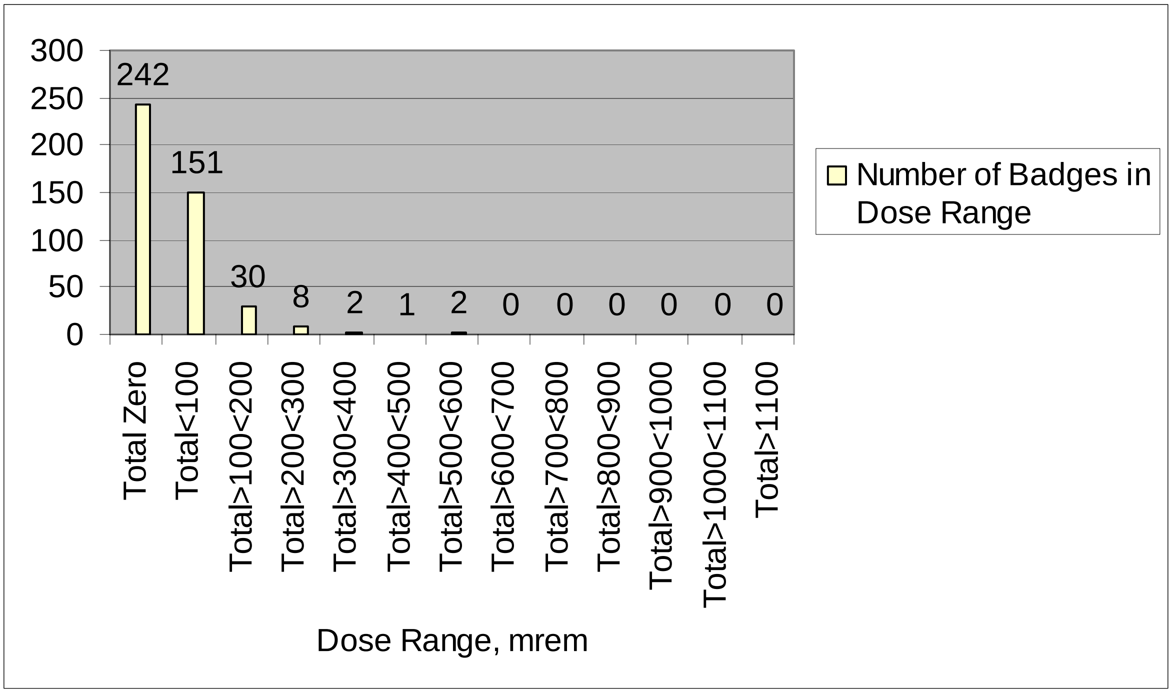
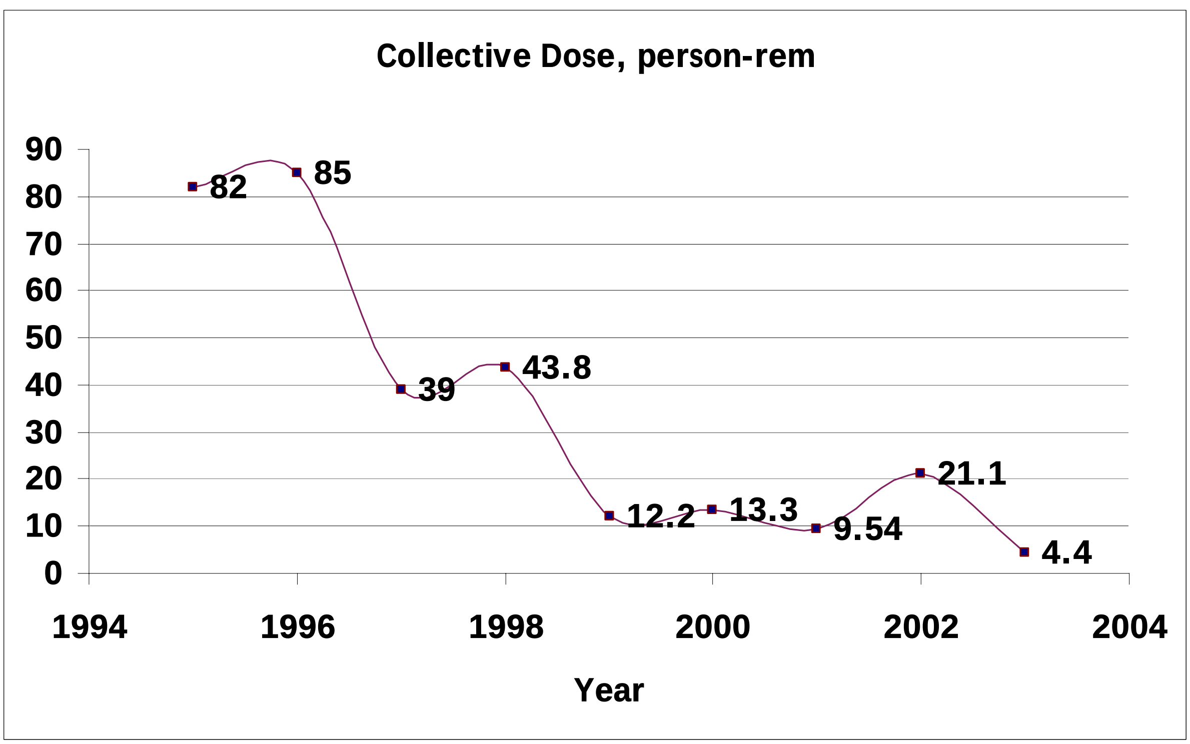


Figure 4.5.13.b Decline in Radiation Worker Dose at C-A Department



Infectious Microorganism Risks

These risks are present at the NSRL. Biological safety cabinets (BSCs) are the primary means of containment developed for working safely with infectious microorganisms. This equipment, located in cell rooms C1 and C2 of the Support Laboratories in Building 958, is appropriate when any work is done with human-derived blood, body fluids or tissues where the presence of an infectious agent may be unknown. Class II Type A BSCs provide personnel, environmental and product protection. Airflow is drawn around the operator into the front grille of the cabinet, which provides personnel protection. In addition, the downward laminar flow of HEPA-filtered air provides product protection by minimizing the chance of cross-contamination along the work surface of the cabinet. Because cabinet air exhaust is passed through a certified exhaust HEPA filter, it is contaminant-free (environmental protection), and may be re-circulated back into the laboratory (Type A), which is the type of BSC employed at cell rooms. CDC standards for BSC testing require an annual test, which includes annual efficiency tests as well as a smoke test and air velocity test. The BSC must maintain a minimum calculated or measured average inflow velocity of at least 75 linear feet per minute at the face opening of the cabinet.

Environmental Risks from Radiation

The only credible risk to the environment is groundwater contamination. This may be caused by a spill of radioactive cooling water from a failed pipe or hose or by an activated soil cap failure, which would allow rainwater to leach the contamination into the aquifer.

An extensive groundwater-monitoring program has been instituted to verify the effectiveness of soil caps and soil-cap maintenance procedures. In accordance with DOE Order 5400.1, General Environmental Protection, groundwater quality down gradient of actual or potential soil activation areas is verified by periodic sampling of groundwater surveillance wells. Groundwater samples are tested for tritium and sodium-22 to verify that the soil caps are effectively preventing rainwater infiltration of activated soil shielding. Sampling frequency for the wells is defined in the annual BNL Environmental Monitoring Plan. The detection of unexpected levels of tritium and/or sodium-22 in groundwater will be evaluated in accordance with the BNL Groundwater Protection Contingency Plan.

The operating procedures, the periodic sampling of onsite drinking water for tritium, the extensive groundwater monitoring program and the long delay times from spill to an onsite or offsite well location preclude the possibility of any worker or member of the public from drinking radioactive groundwater.

Environmental Risks from Biological Materials

There is no credible risk to the environment from airborne releases from the NSRL animal rooms (A1 and A2) in the Support Laboratory, which are Biosafety Level 2. Ventilation is considered a secondary barrier for releases from Biosafety Level 2 facilities. Biosafety Level 2 requirements state, “There are no specific ventilation requirements. However, planning of new facilities should consider mechanical ventilation systems that provide an inward flow of air without re-circulation to spaces outside of the laboratory. If the laboratory has windows that open to the exterior, they are fitted with fly screens."

The NSRL animal laboratories have HEPA filters installed in the room exhaust and in the room re-circulation lines. The requirements for HEPA filtering of exhaust appear in Biosafety Level 3 requirements and even then are only required under certain conditions such as exhausting near occupied areas or ventilation intakes. From this point of view, HEPA testing would not be required since there is no Biosafety Level 2 requirement to have the filters installed. Although testing of HEPA exhaust is not mentioned specifically in the regulations[92], a HEPA filter efficiency test is performed annually.

From a regulatory standpoint, ventilation and exhaust systems for laboratory operations; i.e., lab hoods, are exempt from New York State emission source permitting requirements.

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[92] http://www.cdc.gov/od/ohs/biosfty/bmbl4/bmbl4s3.htm

Fire Risks

Based on the extensive use of fire protection, the appropriate location of exits and the use of emergency ventilation exhaust systems, high or medium consequence levels are extremely unlikely. Thus, the fire risk is acceptable.

The maximum credible fire loss in each C-AD facility is documented in the FHA for each facility in the appendices.

Electrical Risks

Based on the use of formal C-A electrical safety procedures, working hot permits and job safety analyses, high or medium consequence levels are extremely unlikely. Thus, the risk is acceptable.

4.5.14. Professional Judgment Issues

The initial screening of C-AD accelerator and experimental facility hazards was performed using qualitative engineering judgment. The C-A engineering, operating and safety staff has many years of experience with BNL accelerators and experiments. This experience influenced the analyses of Appendix 2.

Experience has also influenced the choice of conservative maximum hourly routine and faulted beam energy limits which have been used as the bases for the shielding and ALARA analyses. These judgment issues have always been and will continue to be verified by beam fault studies.

4.5.15. Methods Used in Evaluation of Radiological Hazards

Techniques employed in the evaluation of radiological hazards include the use of empirical formulae,[93,94,95] and the Monte Carlo Programs MCNPX[96] and CASIM.[97] CASIM has been used satisfactorily at BNL accelerators for many years at energies above 10 GeV, and has been extensively compared to MCNPX at energies above 2 GeV.[98] CASIM cannot be used directly for low-energy neutron transport. It has also been found to overestimate neutron flux in the very forward direction.[99] MCNPX is probably the most widely used neutron transport Monte Carlo code. Several MCNPX calculations have shown excellent agreement with empirical labyrinth formula.[100]

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[93] K. Tesch and H. Dinter, “Estimation of Radiation Fields at High Energy Proton Accelerators,” Radiation Protection Dosimetry, Vol. 15 No. 2 pp. 89-107 (1986).

[94] C. Distenfeld and R. Colvett, "Skyshine Considerations for Accelerator Shielding Design," Nucl. Sci. Eng. Vol. 26, p. 117 (1966).

[95] A. H. Sullivan, A Guide to Radiation and Radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology Publishing, Kent, England, 1992.

[96] L. S. Waters, Ed., “MCNPX USER’S MANUAL,” LANL Report TPO-E83-UG-X-0001, (1999). See also H.G. Hughes, R.E. Prael, R.C. Little, “MCNPX – The LAHET/MCNP Code Merger,” X-Division Research Note, 4/22/97. The version number of the code used in this note is 2.1.5.

[97] A. Van Ginneken, "CASIM; Program to Simulate Hadron Cascades in Bulk Matter," Fermilab FN-272 (1975).

[98] A. J. Stevens, “N-Shield, Description,” BNL C-A Dept. ES&F Division Note 157 (2000). http://server.c-ad.bnl.gov/esfd/epstechnote.html.

[99] See above reference. The CASIM estimates of soil activation in the dump region are in fact over-estimates. Conversely, CASIM dramatically underestimates neutron flux in the backwards direction, but no such estimates exist in the NSRL geometry.

[100] K. Goebel, G.R. Stevenson, J.T. Routi, and H.G. Vogt, “Evaluating Dose Rates Due to Neutron Leakage Through Access Tunnels of the SPS,” CERN LABII-RA/Note/75-10 (1975).

Past measurements by at C-AD accelerators at approximately 90° have been made in BNL soil. They show that dose equivalent and activation calculations are overestimates and should be regarded as upper limits.[101]

The MARS code system is a set of Monte Carlo programs for simulation of three-dimensional hadronic and electromagnetic cascades, and the transport of particles through matter, for particles with energies ranging from a fraction of an electron volt to 100 TeV. This code is expected to be used more often in the future because it includes magnetic and electric field effects on the cascade process. The code is available for the Unix and Linux operating systems, and is distributed by the developers from Fermi National Laboratory.[102]

[101] A.J. Stevens, "Summary of Fault Studies at RHIC." BNL C-A Dept ES&F Note 156 (2000). http://server.c-ad.bnl.gov/esfd/epstechnote.html

[102] The official MARS Web site is http://www-ap.fnal.gov/MARS/, and links there point to many recent applications of the code.